

### Global risk management in a product development project

Jelena Petronijevic

#### ▶ To cite this version:

Jelena Petronijevic. Global risk management in a product development project. Mechanical engineering [physics.class-ph]. HESAM Université, 2020. English. NNT: 2020HESAE034. tel-03004400

### HAL Id: tel-03004400 https://theses.hal.science/tel-03004400

Submitted on 13 Nov 2020

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#### ÉCOLE DOCTORALE SCIENCES DES MÉTIERS DE L'INGÉNIEUR Laboratoire de Conception, Fabrication, Commande – Campus de Metz

# THÈSE

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soutenue le : 22 septembre 2020

pour obtenir le grade de : Docteur d'HESAM Université

préparée à : École Nationale Supérieure d'Arts et Métiers

Spécialité : Génie industriel

### Maîtrise globale des risques dans un projet de développement de produit

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#### Acknowledgement

The thesis presented was conducted under the guidance of Prof. Ali SIADAT and MCf. Alain ETIENNE. Thus, my deepest appreciation goes to them for their scientific advices and observations. This study was about risk and (thus?!) accompanied by a series of unforeseen (risky) events. The continuous encouragement and inventiveness of my superiors in solving challenges is something I can never forget and I will always be thankful for.

I would like to thank Prof. Jean-Yves DANTAN for his scientific discussions and for his support throughout the thesis. I would also like to thank MCf. Lazhar HOMRI for taking care of all the newbies in the lab and for being there to answer every question.

In addition, I would like to thank all the members of my jury: Prof. Elise VAREILLES, Prof. Franck MARLE, MCf. HDR Thierry COUDERT, Prof. Kai FURMANS, Prof. Tyson R. BROWNING and Prof. Didier GOURC. Thank you for the time you have dedicated to my work. Thank you very much for your questions and comments. They made me wonder, and we made progress by wondering.

I would like to express my gratitude to Collège doctoral Franco-Allemand for my scholarship and to Prof. Kai FURMANS for welcoming me into IFL laboratory. I would like to thank Prof. Samuel BASSETTO for welcoming me to his laboratory during my visit to Canada.

I'd like to thank all the LCFC members for making me feel at home.

I would like to thank my LCFC CREW for all the (lunch and other) conversations and the laughter inside and outside the working hours. With this dissertation, not only did I get a degree, but I got buddies!

Finally, I would like to give one (or many) biiiig thank you to MY PEOPLE. To my family for their endless love, care and support. To the one who, during the rainy and sunny days, was the sunshine. To the ones who taught me to push my limits. To those with whom I took my first steps and (even in different countries) with whom I still walk. To those who have always been there to find a solution (and to rationalize my madness). To those who send out good vibrations. To those who are excited about all kinds of ideas I have. To those who made me forget about the problems. To those who make me laugh. Thank you for believing in me even when I don't! You're MY PEOPLE and I am blessed to have you in my life!

#### Хвала вам много!

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### Glossary

This glossary contains the thesis-specific terms and general abbreviations used in the thesis.

ABM	Agent-Based Modelling
Activity	Process (Project) task performed by its actor with certain goal
	using inputs, methods and controls. It generates appropriate
	output(s).
BN	Bayesian Network
Cost risk	Process (Project) output risk illustrating financial problems
COTS	Commercial-Of-The-Shelf (used in System Engineering)
СРМ	Change Prediction Method
Development process;	The thesis focuses on development process as set of tasks
Design;	performed to achieve a defined goal. The terms "process"
	refers to development process with the specific focus on
	design stage of development. Hence, "design" as a process has
	the same meaning as a development process.
DPC	Design Process Change
DSM	Design Structure Matrix
EC	Engineering Change
ЕТА	Event Tree Analysis
FBS framework	Function, Behaviour, Structure framework
FBS linkage	Function, Behaviour, Structure linkage (framework used for
	product decomposition)
FCM	Fuzzy Cognitive Map
FME(C)A	Failure modes, Effect (and Criticality) Analysis
FTA	Fault Tree Analysis
MBSE	Model-Based System Engineering
MC simulation	Monte Carlo simulation
MCA	Multiple Correspondence Analysis
MDM	Multiple-Domain Matrix
PFMEA	Process Failure Modes and Effect Analysis
Product	Product is observed as a result of a development process
	(project) and described with a set of product element and
	components designed to meet customer's requirements.
Product element	Specific product parameter used in the FBS linkage to
	represent product characteristics.
Product performance	"Design performance is defined broadly, including system
	functionality, capability, reliability, price (or life cycle
	operating cost), delivery timing, number of features,
	conformance to specifications, durability, serviceability,
	aesthetics, perceived quality, size, weight, speed, and other
	measures." (Browning, 1998)
Product performance risk	Uncertainty in achieving desired product characteristics in a
	general sense.
Requirement risk	Uncertainty that the presented requirement doesn't represent
	the actual requirements. Requirement risk can also represent
	requirement instability.

<b>RFBS</b> framework	Requirement, Function, Behaviour, Structure framework
Risk factor	Parameter of a development process of a particular interest.
SIR simulation	Susceptible, Infected, Recovered simulation
SysML	Systems Modelling Language
Technology risk	Uncertainty related to the applied technology. It includes wide set of notions from knowledge to it to characteristics.
Time risk	Process (Project) output risk illustrating schedule problems.
UML	Unified Modelling Language
Value risk	Process (Project) output risk illustrating quality of performed
	task or process.

**Résume Étendu En Français** 

#### 1. Introduction

#### 1.1. Définition de la problématique et question scientifique

La gestion des risques lors du développement d'un produit nécessite de garder un œil sur un large nombre de facettes. Du projet au produit, la gestion des risques doit couvrir tous les aspects et fournir des informations adéquates pour la prise de décision.

Bien que la norme (*Risk Management – Risk Assessment Techniques Management Du Risque – Techniques d'appréciation Du Risque*, 2019) s'applique, les problèmes et les surprises causés par des événements inattendus ne sont pas aussi rares qu'on pourrait le penser. En ce sens, on peut se souvenir de deux projets célèbres - Takata et Airbus A380. Dans le problème des airbags de Takata (Tabuchi, 2016), un produit chimique instable, une pratique de fabrication défectueuse et un contrôle de qualité déficient ont provoqué le rappel de 41,6 millions de véhicules aux États-Unis (Consumer Reports, 2019). Dans le cas de la saga de l'Airbus A380, une longueur de câbles a entraîné le retard de ce complexe projet. Des problèmes d'organisation, de communication entre les deux filiales développant l'avion et le manque de flexibilité ont provoqué l'accumulation de problèmes qui ont été identifiés tardivement dans la phase d'assemblage.

Les deux principales observations peuvent être faites sur la base de ces projets. Premièrement, les risques ne sont pas observés de manière globale. Les risques liés au processus de développement et les risques liés au produit sont considérés indépendamment les uns des autres. Comme on l'a vu dans les cas de l'Airbus A380 et de Takata, même si le problème sous sa forme finale peut être représenté dans le produit, l'origine peut être liée au projet. Dans le cas d'Airbus, la raison principale des câbles trop courts n'est pas un problème technique, mais le manque de communication et de coordination entre les départements de développement. Bien que pour Takata, certains puissent dire que l'origine du problème est un produit chimique instable, il ne faut pas oublier que cette information s'est glissée dans le processus de développement et le contrôle qualité. Par conséquent, le processus de développement influence clairement le produit. Mais des observations similaires peuvent être faites en cas d'influence du produit sur le projet. Les pratiques de gestion des risques ne tiennent pas souvent compte de ces interactions, ce qui conduit à des problèmes comme ceux de Takata et d'Airbus.

En résumant les observations de la section précédente, la question scientifique peut être définie comme suit :

Comment évaluer les interactions mutuelles entre les caractéristiques des produits et leurs risques de développement pour permettre la prise de décision et le suivi dynamique ?

#### 1.2. La gestion des risques dans la littérature d'ingénierie

Jusqu'à présent, la nécessité d'une solution intégrée a été identifiée sur la base de la pratique en l'ingénierie. L'identification des lacunes scientifiques serait toutefois incomplète sans une analyse adéquate de la littérature. C'est pourquoi l'étude sur les tendances en matière de gestion des risques en ingénierie dans la littérature a été réalisée. L'objectif est de procéder à une identification impartiale des articles et de fournir un point de vue d'ingénierie sur la gestion des risques.

L'étude a réalisé l'identification des articles à l'aide des mots clés "risque" et "conception". 220 articles ont été identifiés. Dans le rappel de cette sous-section, les principales observations sont présentées.

1. Quelle est la tendance de l'intérêt pour la gestion des risques dans le domaine de l'ingénierie ?

Le nombre de publications par an est présenté dans la figure 1.1-1. Comme on peut le constater, l'intérêt augmente presque exclusivement au cours des dernières années. On peut donc en conclure que l'étude des risques pour l'ingénierie vaut la peine d'être faite.

#### 2. Est-il nécessaire d'adopter des approches générales ?

Pour tous les articles identifiés, le domaine de recherche a été déterminé et le nombre d'articles dans chaque domaine a été reporté sur la figure 1.1-2. Comme on peut le voir, le plus grand nombre d'articles identifiés appartient à la conception générale. On peut donc affirmer que les normes actuelles de gestion des risques, ainsi que la littérature sur la gestion de projet, ne couvrent pas entièrement la demande. En ce qui concerne cette thèse, elle montre que la lacune scientifique est présente et nécessite une étude plus approfondie pour donner des informations détaillées sur des besoins.

#### 3. Comment le risque est-il défini dans la littérature technique ?

Cette question porte sur la définition du risque et sa différenciation entre sécurité et non-sécurité, d'une part, et son utilisation avec d'autres termes tels que l'incertitude, la probabilité, la robustesse et la fiabilité, d'autre part. L'étude montre que les risques sont encore souvent observés comme des dangers. La terminologie des risques communs comparée aux différents cas d'utilisation est présentée dans la figure 1.1-3. Comme on peut le voir, les différentes notions de risque sont présentes de manière presque égale dans les différents groupes.

#### 4. Comment les approches du risque soutiennent-elles l'ingénierie ?

La répartition des différents cas d'utilisation est présentée à la figure 1.1-4. 74 % de tous les articles demandent une solution décisionnelle par optimisation, décision générale ou particulière. Cela implique que la communauté a besoin de solutions pour traiter le risque. Cependant, il ne faut pas négliger le fait que 15 % et 34 % des articles appartiennent à la catégorie des optimiseurs et des solveurs de problèmes particuliers. Cela signifie que potentiellement près de 50 % des articles identifiés ont, sous une forme ou une autre, une définition problématique du risque et de l'utilisation au sens de la gestion standard des risques.

#### 5. Quelle est la maturité des solutions développées ?

Les résultats sont présentés dans la figure 1.1-5. La plupart des solutions sont développées sous forme d'outils (56%). Cela peut être interprété de deux manières. Le domaine de l'ingénierie a besoin d'outils adéquats. En d'autres termes, soit les approches actuelles doivent être adaptées, soit elles ne couvrent pas tous les besoins actuels. Cependant, la question qui doit être posée ici encore est l'influence de l'optimisation, des solutions particulières et de la définition commune des risques. Cette question sera traitée plus en détail à la question 7.

#### 6. Quelle est la phase de gestion des risques la plus traitée ?

Les résultats de l'analyse sont présentés dans la figure 1.1-6. Il n'est pas surprenant de constater que 40 % des articles appartiennent à la catégorie "aucun". Ce nombre est constitué en grande majorité d'articles traitant de problèmes particuliers. Comme ils n'ont que peu ou pas de rapport avec la gestion des risques, ils n'abordent aucune phase. En dehors de ces articles, 15% des solutions sont orientées vers l'optimisation et ne traitent que de l'évaluation. Cela implique que l'orientation vers le risque est présentée dans moins de 50% des articles dont le titre comporte le mot-clé "risque" ! En se concentrant sur ces articles, il est intéressant de noter que 25 % de tous les articles traitent de la phase d'évaluation. Ainsi, les plus grands efforts de la communauté sont faits pour fournir des solutions qui couvriront

l'identification, l'analyse et l'évaluation des risques. Cela peut donc indiquer l'orientation possible de la thèse.

#### 7. Quel est le lien entre les différents aspects ?

Pour répondre à cette question et à d'autres questions sur les relations entre différents aspects, une analyse par correspondances multiples (ACM) a été réalisée. Deux observations principales concernant l'orientation de la recherche de la thèse peuvent être formulées (figure 1.2). Premièrement, comme prévu, l'optimisation et les problèmes particuliers sont résolus sous forme d'outils. Comme la prise de décision est généralement abordée par le biais de méthodologies, il est clair que la solution logicielle générale est nécessaire. Deuxièmement, ces solutions demandent des approches statistiques ou axées sur les données. Cela se justifie par le fait que, jusqu'à présent, ces solutions n'incluent pas, pour la plupart, de terminologie commune. Par conséquent, le risque est généralement identifié uniquement avec l'aide d'experts et peut souvent être décrit de manière qualitative ou quasi-quantitative. Par conséquent, la thèse peut se concentrer sur l'approche générale qui doit être formée comme un outil qui peut soutenir l'analyse statistique.

Si l'étude générale de la gestion des risques en ingénierie a fourni un bon aperçu dans ce domaine, elle a également suscité des interrogations sur les approches générales de prise de décision. Une nouvelle étude a été menée et les résultats sont présentés dans le tableau 1.2. Les résultats montrent l'absence de liens entre les processus, le projet et le produit. La communauté travaille sur différentes relations en matière de gestion des risques, mais il reste du chemin à parcourir. Enfin, la nécessité de trouver des solutions pour soutenir la prise de décision est évidente. Tout cela justifie la motivation de travaux de la thèse.

#### 1.3. Méthodologie de recherche

L'observation séparée des risques liés au projet (voir 1 dans la figure 1.5) et au produit (voir 2 dans la figure 1.5) peut être comparée au développement d'une seule partie du produit final. Bien que cela puisse être considéré comme suffisant pour représenter certaines caractéristiques d'un produit, sa fonctionnalité complète ne peut pas être atteinte. Les fils de contact d'une ampoule ont besoin d'un filament pour les connecter. On peut en dire autant de la gestion des risques. Sans connexion entre le processus et le produit (voir 3 dans la figure 1.5), la gestion des risques ne résout que partiellement le problème. En outre, comme l'a montré brièvement l'analyse documentaire réalisée, les solutions actuelles ne couvrent que partiellement les problèmes du processus et de produits dans la gestion des risques. Par conséquent, le but de cette thèse est d'abord d'approfondir les différents modèles en représentant les interactions au sein du processus (voir 4 dans la figure 1.5) et du produit (voir 5 dans la figure 1.5). Sur ces solutions individuelles, les liens doivent être établis (voir 6 dans la figure 1.5). On pense que cette connexion permettra d'avoir une meilleure perspective de la gestion des risques dans les projets de développement de produits.

Compte tenu de tout ce qui précède, la méthodologie de recherche comprend cinq parties :

- Première partie : Aperçu général du risque, des lacunes scientifiques et des principales exigences de la future solution.
- Partie 2 : Développement d'un simulateur de gestion des risques pour un projet ou un processus de développement.
- Partie 3 : Développement d'un simulateur de gestion des risques pour un produit.
- Partie 4 : Développement d'un simulateur de gestion des risques pour un projet ou un produit général en fusionnant les deux solutions individuelles. Représentation claire des liens entre un processus de développement et son produit.

• Partie 5 : Étude de cas sur une solution développée.

La première partie est couverte par la section 1. Les deuxième, troisième et quatrième parties sont couvertes respectivement dans les sections 2, 3 et 4. Enfin, chaque partie de la solution (projet, produit ou général) est illustrée par un exemple.

#### 1.4. Contributions attendues et limites de la thèse

Chronologiquement parlant, la première contribution de la thèse est la réalisation d'une étude générale de l'état de l'art. En dehors de ce qui est mentionné, les contributions de la thèse peuvent être divisées en trois catégories principales : les contributions liées à la gestion des risques du projet, celles liées au produit et celles imposées par les liens entre le projet et le produit dans la gestion des risques. Cependant, ces trois aspects contribuent à l'exhaustivité, la flexibilité et la représentation des connexions.

Certaines limites existent en termes de gestion des risques, de définition des risques et d'application. L'approche du risque développée n'inclut pas toutes les phases de la gestion du risque. Elle considère la phase qui est au centre de la majorité des approches d'ingénierie - l'évaluation des risques. En termes de définition du risque, il convient de souligner que l'approche ne tient pas compte explicitement des défaillances. En termes de définition du projet, ce dernier est observé comme un processus de développement. Enfin, en termes d'application, il convient de noter que du point de vue de l'utilisateur, l'effort initial est nécessaire pour définir le comportement de développement. La solution est générale, et peut donc être adaptée à différents processus de développement après cette étape, mais l'utilisateur est l'expert qui doit fournir les connaissances adéquates pour adapter la solution au problème observé. Les travaux futurs porteront sur l'introduction de techniques d'exploration de données et d'apprentissage qui peuvent contribuer à l'automatisation de cette étape.

## 2. Du framework au simulateur pour la gestion des risques dans un processus de développement

### 2.1. La gestion des risques dans le développement de produits : des définitions à l'état de l'art

Dans la norme ISO 31000, le risque représente un effet de l'incertitude sur les objectifs. Selon la norme ISO 31010, le risque (effet) peut être décrit comme une chaîne de termes comprenant la source du risque, l'événement, la conséquence et la probabilité. La figure 2.1 illustre cette chaîne. C'est cette terminologie qui est utilisée dans la thèse.

L'incertitude est un attribut d'un événement et un effet dans la littérature sur la gestion des risques. Elle représente l'insuffisance d'information, de compréhension ou de connaissance liée à chaque terme (31000: Risk Management — Principles and Guidelines, 2009). Cependant, différents domaines considèrent l'incertitude de manière différente. Le tableau 2.1 résume les taxonomies que l'on peut trouver dans les domaines considérés comme liés au sujet de la thèse. Ces différents types d'incertitude concernent différents aspects de la thèse. Tout d'abord, à partir de la séparation fondamentale entre aléatoire et épistémique, on peut faire la distinction entre les événements à risque individuels et le comportement d'un processus de développement. D'autres types d'incertitudes de Thunnissen (2003) sont également représentés dans la thèse. L'ambiguïté est intégrée en considérant l'imprécision des exigences. Enfin, la partie centrale de la thèse est basée sur l'incertitude des interactions.

Les techniques de représentation des conséquences et de la probabilité, ainsi que des dépendances et des interactions, sont résumées dans le tableau 2.2. La classification est basée sur la norme ISO 31010

et est choisie en fonction de leur capacité de représentation quantitative du risque ou du lien entre le quantitatif et le qualitatif.

De même que pour la conclusion de l'étude de la première section, on peut dire qu'une seule méthode ne peut pas couvrir tous les aspects que la thèse aborde : les mesures qualitatives pour la probabilité et la conséquence et l'inclusion des interactions. Bien que différentes solutions abordent les conséquences de manière numérique, le principal problème est qu'elles sont basées sur des scénarios, l'accent étant mis sur la détermination de la probabilité de l'effet. Ainsi, les différents effets sont dans ces cas prédéterminés et ne sont pas explicitement liés au comportement du système.

Pour tenir compte des différents objectifs fixés par le fossé scientifique, les articles ont été étudiés sous l'angle du processus de développement et de la représentation du comportement à risque et de la propagation du risque. Les articles les plus pertinents sont présentés dans le tableau 2.3.

Tout d'abord, on peut remarquer que les processus sont rarement traités dans la gestion des risques. Les solutions où le processus n'est pas pris en compte, représentent les risques de manière indépendante ou globale. Dans ce cas, le risque n'est pas modélisé sur les niveaux inférieurs au projet lui-même, d'où l'impossibilité d'en observer la propagation à l'intérieur de celui-ci. Ces solutions comprennent les réseaux bayésiens, les cartes cognitives floues ou la propagation basée sur des graphes (Jamshidi et al., 2018a ; Kayis et al., 2006 ; Lazzerini & Mkrtchyan, 2011 ; Shojaei & Haeri, 2019). Toutefois, ces modèles peuvent être utilisés pour traiter le processus. Pour remédier à l'absence de propagation explicite des risques dans le processus, les modèles de chaîne de valeur peuvent être utilisés (Bosch-Mauchand et al., 2012 ; Tyson R Browning & Eppinger, 2002 ; L. A. Shah et al., 2016). En termes de comportement, un autre groupe d'approches peut être identifié - celui qui traite du dynamisme et des acteurs impliqués dans le projet. Ces solutions sont basées sur des systèmes multi-agents pour s'adapter aux besoins spécifiques du modèle (Kayis et al., 2006 ; Rodney et al., 2015a).

Compte tenu de tout ce qui précède, la solution qui peut répondre pleinement à la question scientifique n'a pas été identifiée. Cependant, différentes solutions montrent un potentiel pour traiter un aspect spécifique du problème observé. Leur utilisation dans différents aspects de la thèse est résumée dans le tableau 2.4.

L'intégration de toutes les méthodes mentionnées dans une approche commune est unique et n'est pas identifiée dans la littérature. L'approche, depuis son framework, en passant par le simulateur jusqu'à l'application basée sur l'exemple académique, est donc présentée dans la suite de cette section.

### 2.2. La gestion des risques dans un processus de développement - le framework proposé et son modèle

Dans ce travail, les causes ou les risques sont considérés séparément d'un processus de développement. Le processus de développement est observé comme un système (complexe) dont le résultat représente un effet du risque sur l'objectif. Cette idée principale est illustrée dans la figure 2.3.

Comme on peut le voir, les événements à risque (voir 1 dans la figure 2.3) affectent le comportement d'un système (voir 2 dans la figure 2.3). Cet événement peut être n'importe quelle circonstance externe pouvant entraîner le changement d'un système. En ce qui concerne la situation actuelle dans le monde, il peut s'agir d'un blocage en Chine entraînant un problème de disponibilité d'un fournisseur impliqué dans le processus de développement observé. L'influence de cet événement et de tout autre événement à risque est considérée comme un comportement du système. Afin de comprendre ce comportement, les éléments mentionnés peuvent être divisés en paramètres ou facteurs de risque (voir 3 dans la figure 2.3). Un paramètre peut en influencer un autre (voir 4 dans la figure 2.3) et, ensemble, ils forment un

graphique ou un réseau de relations interconnectées. Le résultat de ce réseau est le risque de sortie ou l'effet ciblé sur les objectifs (voir 5 dans la figure 2.3). Cette manière de décomposer les risques de processus peut donner des informations plus détaillées sur les objectifs, car ils sont considérés comme faisant partie du comportement d'un système. Dans ce travail, le risque de production est un paramètre du système qui présente un intérêt particulier. Par conséquent, il évolue en même temps que le comportement global. En ce sens, même le paramètre qui n'est pas considéré comme un risque de production dans une optique peut être observé comme l'objectif dans une autre sans que la structure du modèle ne soit modifiée.

Comme indiqué précédemment, l'objectif de ce travail est de permettre une intégration et une interaction ascendantes du risque, en distinguant clairement les événements à risque des comportements à risque. Pour passer d'une idée générale au framework, plusieurs concepts ont été inclus et reliés entre eux. Ils sont représentés dans la figure 2.4.

Le processus de développement a été divisé en tâches (voir 1 dans la figure 2.4). On suppose que ces tâches, tout comme les parties du système complexe, peuvent être normalisées pour la plupart des processus de développement. En fonction de son type, la tâche peut avoir son risque (général) (voir 2 dans la figure 2.4). Le risque est décomposé en un ensemble de facteurs de risque (voir 3 dans la figure 2.4) qui sont considérés comme importants pour le type de tâche. Chaque facteur de risque a sa valeur initiale qui dépend d'un ou plusieurs événements de risque (voir 4 dans la figure 2.4). Ces événements sont tous représentés avec leur probabilité (voir 5 dans la figure 2.4) et leur gravité (voir 6 dans la figure 2.4). Chaque facteur de risque est lié à au moins un autre. Ce réseau de facteurs de risque forme le comportement de risque de la tâche (voir 7 dans la figure 2.4). En raison de la perturbation de la valeur d'un ou de plusieurs facteurs, le risque progresse à travers le réseau de facteurs, ce qui entraîne le changement de l'objectif du processus de développement. L'objectif peut être le coût, le temps, la qualité ou tout autre paramètre d'intérêt pour l'acteur et le processus de développement. Ce facteur est appelé "risque de sortie de tâche" (voir 8 dans la figure 2.4). Le processus de développement (voir 9 dans la figure 2.4) est composé de tâches. Le risque de sortie du processus de développement (voir 10 dans la figure 2.4) est donc le résultat de la dernière tâche effectuée dans le processus qui a pris en compte toutes les tâches précédentes. Ces principaux concepts sont soutenus par les méthodes de modélisation adéquates, figure 2.5.

L'illustration du modèle est présentée à la figure 2.6. Comme on peut le voir en 1 dans la figure 2.6, l'agent « activité » est le porteur de l'information et du comportement en matière de risque. Conformément à l'ingénierie des systèmes, un agent d'activité possède tous les éléments que l'on peut voir dans l'approche SADT (IDEF0). Divisées par types, les ressources sont représentées sous forme d'agents et les méthodes sous forme de valeurs (voir 2 et 3 dans la figure 2.6). L'agent de ressource comprend l'équipement et tous les acteurs, externes et internes, inclus dans le processus.

Les entrées (voir 4 dans la figure 2.6) et les contrôles (voir 5 dans la figure 2.6) sont représentés comme des facteurs de risque. Par conséquent, ils ont une valeur entre 0 et 1 indiquant leur qualité. La valeur 0 signifie l'absence de problèmes et la valeur 1 indique des problèmes importants. Les entrées et les contrôles peuvent être indépendants ou dépendre du processus de développement. Les entrées et contrôles dépendants sont le résultat des interactions et des relations des activités menées précédemment. Par conséquent, ils ne peuvent pas être modélisés uniquement comme aléatoire mais doivent prendre en compte l'incertitude des interactions. Pour cette raison, les dépendances entre et au sein des tâches doivent être modélisées. Ce lien est défini à l'aide des sorties (voir le point 6 de la figure 2.6). Les utilisateurs peuvent définir leurs propres sorties (et les facteurs de risque en général), cependant, dans ce travail, on considère que le risque de coût, de temps et de valeur peut être utilisé

pour représenter toutes les relations souhaitées. Le risque de valeur représente la qualité de la performance de la tâche. L'activité suivante utilise la valeur de sortie de la tâche précédente comme entrée.

Une fois que les dépendances entre les tâches ont été expliquées, c'est le lieu de représenter les dépendances au sein d'une tâche. Les dépendances forment le comportement de risque de la tâche et entraînent le risque de sortie de la tâche en utilisant des cartes cognitives floues (Fuzzy Cognitive Maps) (voir 7 dans la figure 2.6). Fuzzy Cognitive Map (FCM) est un graphique dirigé dont les nœuds représentent les valeurs des facteurs de risque (voir 8 dans la figure 2.6) et les arcs pondérés quantifient les interactions entre ces facteurs. La FCM est donc utilisée pour calculer la gravité du risque. La FCM calcule de nouvelles valeurs de facteurs de risque (sévérité) sur la base des valeurs initiales.

Les valeurs initiales des facteurs de risque sont obtenues de trois manières. Si un facteur de risque est une entrée ou un contrôle dépendant, sa valeur initiale dépend des relations de priorité entre les activités. Le résultat d'une activité d'entrée définit directement la valeur. Si un facteur de risque est une entrée ou un contrôle indépendant, sa valeur est jugée "telle quelle", généralement par un ou plusieurs experts. Enfin, les valeurs initiales des facteurs de risque dépendent des événements à risque. L'agent de risque (voir 9 dans la figure 2.6) est utilisé pour représenter les événements de risque (voir 10 dans la figure 2.6). Globalement, les événements peuvent être divisés en deux catégories : les événements standard et les événements dangereux. Les événements dangereux ont un impact direct sur le risque de sortie, ils sont épistémiques et peuvent être considérés comme un "risque de surprise". Leur probabilité n'est pas connue avec précision, mais elle est considérée comme faible. L'effet, en revanche, peut être grave. Ils sont modélisés comme des événements aléatoires. Les événements de risque standard influencent les autres facteurs de risque. Leurs probabilités sont connues, et les sévérités sont représentées de manière discrète. Comme plusieurs événements peuvent avoir un impact sur le même facteur, ils peuvent être représentés sous la forme d'un réseau bayésien (voir 11 dans la figure 2.6).

## 2.3. Gestion des risques dans un processus de développement - concept d'une solution logicielle

Guidé par l'idée générale, le modèle peut être divisé en deux parties : modèle externe (causal) des événements à risque et modèle interne (comportement à risque). Ce lien est illustré dans la figure 2.9. Les événements externes sont modélisés dans le logiciel dédié aux réseaux bayésiens (BN) : UnBBayes. La principale solution logicielle est basée sur la modélisation basée sur les agents (ABM) dans AnyLogic. Excel est utilisé pour stocker les données d'entrée nécessaires à la solution principale.

La structure complète d'un simulateur de risques proposé est présentée à la figure 2.10. Comme expliqué dans la sous-section précédente, le simulateur se compose de deux parties. Le premier est décrit par l'événement, le lien bayésien et le réseau de risque dans la figure 2.10 et le modèle dans le logiciel UnBBayes. Le reste du logiciel est modélisé dans l'environnement ABM.

La solution logicielle comprend plusieurs agents et les fonctions se coordonnent pour obtenir le risque de sortie. Afin de bien comprendre son fonctionnement, il est nécessaire de connaître les séquences d'exécution : séquence du risque (figure 2.11), séquence de l'activité (figure 2.12) et comportement de l'activité (figure 2.13).

### 2.4. Gestion des risques dans un processus de développement - utilisation de la solution

La norme ISO (*31000: Risk Management — Principles and Guidelines*, 2009) comprend trois processus d'évaluation des risques : l'identification des risques, l'analyse des risques et l'évaluation des risques. Ces trois processus dans le contexte du simulateur développé et de son utilisation sont présentés dans la figure 2.15.

Avant d'utiliser le simulateur, plusieurs étapes doivent être effectuées manuellement. Tout d'abord, l'identification des risques doit être effectuée. Dans le contexte de la solution développée, cette étape comprend l'identification ou les facteurs de risque. Pour ce faire, l'utilisateur ou l'analyste des risques peut commencer à partir d'un projet antérieur et de la documentation des risques, en particulier du registre des risques. Afin de définir les facteurs de risque, l'utilisateur doit regrouper les risques dans des catégories communes en fonction de leur influence. Par exemple, tous les événements de risque ayant un impact sur la disponibilité du travailleur seront regroupés sous le même facteur de risque.

Après l'identification, l'analyse des risques doit également être effectuée manuellement. L'analyse des risques prend en compte les causes de risques ainsi que leurs conséquences. Dans le contexte du simulateur développé, ce processus porte sur la création d'un réseau d'événements externes (réseau bayésien) et d'une carte cognitive floue. Il est réalisé en trois étapes : l'identification du réseau de risques, l'identification du réseau d'événements et la définition du comportement risque.

L'étape de définition du réseau vise à identifier les relations entre les facteurs de risque préalablement définis. Ce processus est à nouveau effectué par l'analyste des risques en utilisant des techniques de regroupement et des informations provenant du registre des risques. En d'autres termes, au cours de cette étape, l'utilisateur passe une fois de plus en revue les événements dans le registre des risques. Chaque fois que l'influence d'un facteur de risque sur un autre a été identifiée, le lien entre le facteur de risque est établi.

Une fois que l'ensemble du registre des risques a été couvert et que toutes les relations entre les facteurs ont été notées, le réseau d'événements à risque doit être établi. Le réseau d'événements à risque est un réseau bayésien formé de chaque facteur de risque afin de définir les probabilités pour différentes sévérités. Comme pour les étapes précédentes, ce réseau peut être créé sur la base du registre des risques et du réseau de risques défini précédemment. Cette fois, les événements à risque ayant un impact direct sur un facteur de risque particulier sont identifiés et reliés en un réseau.

Dans la troisième étape de l'analyse des risques, les pondérations sont attribuées au réseau de risques précédemment défini. Ce processus finalise le comportement à risque en complétant toutes les informations nécessaires à la construction de la carte cognitive floue (Fuzzy Cognitive Map). L'évaluation des risques au niveau d'une tâche et d'un processus est effectuée dans le simulateur développé dans ces travaux.

Il ne faut pas oublier que les étapes manuelles doivent être effectuées pour tous les types d'activités impliquées dans le processus de développement. Bien que cela puisse sembler être une tâche fastidieuse, il est nécessaire de mentionner que le nombre de types de tâches est sensiblement inférieur au nombre d'activités réelles. Dans la section 4, 4 types de tâches sont utilisés pour décrire toutes les activités identifiées dans le processus de conception.

#### 2.5. Exemple de la solution proposée

Après avoir vu la solution proposée de l'idée au simulateur développé, l'objectif est de vérifier son utilisation à travers l'exemple qui pourrait être vu en pratique. Le processus de développement à petite échelle a été fait. L'objectif du processus est de développer un nouveau sèche-cheveux. Le développement se concentre sur la proposition de solution initiale et ses risques. La structure du processus de développement est présentée à la figure 2.17 et les activités et leurs informations connexes sont présentées au tableau 2.5. Les informations sur les risques utilisées pour la gestion des risques sont basées sur les registres des risques existants que l'entreprise possède. Dans cet exemple, la liste des risques de Kendrick est utilisée comme un registre des risques. L'ensemble de la liste est utilisé pour modéliser le comportement à risque (c'est-à-dire la carte cognitive floue). Toutefois, étant donné que l'objectif de cet exemple est d'illustrer les principales fonctions du modèle et en raison du manque de probabilité et de gravité dans le registre mentionné, le nombre de risques utilisés pour modéliser le réseau d'événements à risque (réseau bayésien) et les événements dangereux est limité et présenté dans la première colonne du tableau 2.6.

L'identification et l'analyse des risques sont effectuées manuellement de la même manière que celle expliquée dans la sous-section précédente. Les figures 2.18, 2.19, 2.20, 2.21 et les tableaux 2.7 et 2.8 illustrent ces étapes.

L'évaluation des risques est effectuée dans le simulateur développé. La prédiction des risques est effectuée d'abord au niveau des tâches et ensuite au niveau des processus. L'outil principal utilise les informations de la base de données contenant des informations sur le processus de développement et les données sur les risques obtenues du logiciel UniBBayes. Les résultats comprennent les risques de coût, de temps et de valeur pour chaque activité. Le coût du processus est calculé comme une somme des coûts individuels. En ce qui concerne le risque temporel, chaque activité individuelle garde une trace de son heure réelle de début et de fin en fonction des risques considérés. Ainsi, l'heure de fin de la dernière activité représente l'heure de fin du processus. Les valeurs individuelles sont incluses dans les activités suivantes par le biais de relations séquentielles et du comportement des tâches. Ainsi, l'activité en cours indique la valeur globale du processus. Les résultats sont présentés dans les tableaux 2.10, 2.11 et 2.12.

Le tableau 2.10 indique le coût, le temps et la valeur réels de chaque activité obtenus au cours d'une simulation. Les résultats sont basés sur l'état stable obtenu pour chaque activité.

Pour une analyse plus approfondie du comportement, les vecteurs de production non normalisés sont présentés dans le tableau 2.11. Toutes les activités ayant des FCM identiques sont colorées dans les mêmes couleurs. Ici, il est clair que toutes les activités partageant la même carte cognitive floue ont atteint le même point fixe.

La même expérience a été réalisée mais cette fois avec le numéro d'itération de la FCM pris aléatoirement. Les numéros d'itération ont été répartis uniformément entre 1 et 27. La limite supérieure est fixée en gardant à l'esprit que l'état stable est généralement atteint en 26 itérations. Les résultats obtenus sont présentés dans le tableau 2.12. Les résultats confirment que la FCM converge rapidement vers son point fixe.

Enfin, on peut conclure que l'outil développé peut représenter différents états du système.

#### 2.6. Gestion des risques dans un processus de développement - conclusions

Compte tenu de tout ce qui précède, les principales contributions peuvent être résumées comme suit :

- La solution globale est fournie pour les interactions de risque dans le processus de développement.
- Les événements de risque sont séparés du comportement de risque permettant une vue statistique et systémique sur les risques.
- Plutôt que de se concentrer sur la détermination des seules probabilités ou effets, la solution permet de calculer à la fois les effets et les probabilités. L'effet comprend des nuances entre les états stables et chaotiques, tandis que la combinaison du réseau bayésien et de la simulation de Monte Carlo est utilisée pour représenter les probabilités de différents événements et de leurs effets.
- Comme le risque est modélisé au niveau de la tâche, la solution fournit le moyen d'une intégration ascendante du risque. Ainsi, l'utilisateur qui dispose d'un développement pratique peut participer directement à la gestion du risque.
- La solution peut être utilisée comme modèle pour différents processus de développement.
- Le simulateur permet une analyse « what if » et multi-vues.
- 3. Cadre et simulateur pour les risques liés aux produits dans un contexte de développement

### **3.1.** Gestion des risques pour les produits en cours de développement : des hypothèses à l'état de l'art

Habituellement, les risques liés aux produits sont observés seuls, en approfondissant l'aspect sécurité et les analyses de défaillance. Dans la thèse, cependant, le produit fait partie du processus de développement. L'objectif de la gestion des risques liés au produit est de fournir des informations sur l'évolution des risques liés au produit en prenant en compte les problèmes liés au produit lui-même mais aussi ceux issus du processus de développement. Ce problème spécifique nécessite donc une définition adéquate du risque produit qui en résulte et de la terminologie des risques correspondante. C'est pourquoi cette sous-section traite de ces principales hypothèses.

Le risque lié au produit est observé à travers les performances du produit. Le risque de performance est "l'incertitude quant à la capacité d'une conception à répondre aux critères de qualité souhaités" (Tyson R. Browning, 1999).

Afin de permettre cette prévision, différents facteurs et leur influence sur la performance sont observés (Tyson R. Browning, 1998, 1999) : processus d'évaluation, temps et coût, itérations, approbations, complexité du produit, définition du risque, couplage et technologie avec sa maturité et les connaissances connexes obtenues par le personnel concerné. Les facteurs, leurs relations et l'influence du risque lié à la performance du produit sont présentés dans la figure 3.1.

Tout comme le processus de développement, le produit est observé comme un système et, dans ce sens, il est décomposé en sous-éléments (composants, pièces, etc.). Le risque de performance du produit complet est obtenu sur la base des valeurs de ces composants individuels et de leurs interactions. En ce sens, les interactions doivent être correctement traitées.

En gardant à l'esprit tout ce qui précède, deux questions principales doivent être examinées afin de fournir une solution adéquate de gestion des risques pour le produit en cours de développement. Premièrement, quelle est la décomposition adéquate du produit ? Deuxièmement, quelles sont les relations entre les éléments du produit qui peuvent représenter l'interaction et la propagation du risque d'un élément à l'autre et d'un niveau inférieur à un niveau supérieur ?

La solution identifiée dans la littérature sur le changement est celle qui convient le mieux à la décomposition du produit. Selon la théorie de la conception, le cadre FBS présente le plus grand potentiel de décomposition des produits puisqu'il couvre tous les aspects d'un produit. Grâce à cette approche, le produit peut être représenté par différents ensembles de paramètres de conception. Pour cette raison, les approches basées sur des paramètres de conception généraux peuvent également être utilisées dans le contexte de la thèse (voir le tableau 3.3 - décomposition du produit).

Les réseaux sont identifiés comme une base importante pour la propagation des défaillances et des changements. En même temps, ils présentent le plus grand potentiel pour représenter les connexions entre les différents aspects du produit et leurs paramètres.

En termes de propagation, l'approche choisie est la simulation basée sur les agents.

Étant donné que les événements à risque et leur propagation sont inconnus, la solution basée sur l'agent avec simulation SIR (Susceptible – Infected – Recovery) est considérée comme la plus adéquate. On considère que le SIR peut fournir le caractère aléatoire nécessaire au modèle.

## **3.2.** Gestion des risques pour les produits en cours de développement - le framework proposé et le modèle

L'idée principale est présentée dans la figure 3.3. Différentes causes (voir 1 dans la figure 3.3) peuvent entraîner les changements liés à un élément individuel du produit (voir 2 dans la figure 3.3). Ces changements peuvent être négatifs ou positifs. Le négatif implique la génération d'un problème sur l'élément individuel du problème, tandis que le positif représente les solutions au problème. Ainsi, deux influences principales peuvent être observées dans l'élément individuel du produit : le problème et sa solution. Les éléments de produit sont reliés entre eux sur la base de dépendances de nature différente : informations, lois physiques, relations avec les concepteurs ou autres. Comme les causes entraînent la modification des valeurs de différents paramètres de l'élément de produit, ces nouvelles valeurs peuvent entraîner des problèmes dans d'autres éléments du produit en fonction des connexions établies entre les éléments. La propagation des problèmes n'est pas déterministe, mais plutôt aléatoire et dépendante des connexions, des probabilités et de la sensibilité entre les éléments. Les connexions et la propagation peuvent être vues au point 3 de la figure 3.3. Ainsi, la performance de l'élément individuel dépend non seulement des causes qui l'affectent directement, mais aussi des autres éléments avec lesquels il est en contact direct ou indirect. Par conséquent, le risque se propage d'un élément à l'autre et constitue un risque de performance du produit (voir le point 4 de la figure 3.3). Dans ce travail, le risque de performance du produit est observé à travers les valeurs des performances individuelles.

Contrairement à la gestion du risque processus, l'objectif de la solution produit n'est pas de considérer tous les événements de risque individuels et leur influence sur la performance. L'identification des facteurs influents est basée sur le cadre de Browning et comprend l'influence des tâches de conception, des exigences et de la technologie (Figure 3.4). Ces trois facteurs peuvent être attribués à chaque élément du produit. Cependant, ils se propagent individuellement.

La figure 3.6 présente un modèle de risque général pour la prédiction du risque lié à la performance des produits. L'élément central du modèle est l'élément produit, présenté en 1 dans la figure 3.6. Il est modélisé comme un agent. L'élément produit est basé sur l'ontologie FBS (Hamraz et al., 2012, 2015).Il peut, donc, être : structurel, comportemental ou fonctionnel, avec tous les détails nécessaires.

L'élément de produit présente des facteurs de risque (voir 2 dans la figure 3.6) qui forment le risque de performance de l'élément de produit (voir 3 dans la figure 3.6). Les facteurs de risque sont des variables de l'agent de l'élément de produit. Ils sont initialement définis mais ils évoluent également au cours de

l'exécution du modèle. Les facteurs de risque sont définis sur la base du cadre proposé et comprennent des paramètres de technologie, d'exigence et de valeur (marqués respectivement aux points 4, 5 et 6 de la figure 3.6).

La valeur actuelle de toutes les variables, mais aussi les performances du produit sont représentées en utilisant la gravité. La gravité peut être satisfaisante ou insatisfaisante. La gravité satisfaisante (voir le point 8 de la figure 3.6) implique qu'aucun problème n'est rencontré et que, par conséquent, aucune tâche supplémentaire n'est nécessaire. La gravité insatisfaisante (voir 9 dans la figure 3.6) indique qu'il y a un problème et qu'il faut donc trouver une solution (voir 10 dans la figure 3.6). La solution modifie directement la valeur de gravité d'un ou plusieurs facteurs de risque et le risque de performance des éléments du produit. Ce changement dépend de la performance d'itération (voir 11 dans la figure 3.6) qui est définie soit pour chaque activité, soit au niveau du produit. Par exemple, on peut affirmer que chaque itération supplémentaire améliore la solution de 20 %. Dans ce cas, la performance d'itération est fixée à 20 %.

La solution au problème n'est qu'une façon de modifier les degrés de gravité. L'autre est basée sur la propagation de problèmes ou de solutions à partir d'autres éléments du produit. Afin de permettre cette propagation, chaque élément de produit peut avoir une ou plusieurs connexions (voir 12 dans la figure 3.6). La connexion entre les deux éléments est décrite à l'aide de la probabilité et de la sensibilité. La sensibilité (voir 13 dans la figure 3.6) décrit la sensibilité d'un élément sur les changements de l'élément connecté (élément parent). Ici, les changements comprennent à la fois les problèmes et les solutions. La probabilité (voir 14 dans la figure 3.6), en revanche, définit la probabilité que le problème ou la solution se propage à l'élément de produit particulier.

Comme le produit ou le système (voir 15 dans la figure 3.6) est composé d'éléments de produit, les problèmes et solutions apparaissant à ce niveau forment directement le risque de performance du produit ou du système (voir 16 dans la figure 3.6).

## **3.3.** Gestion des risques pour les produits en cours de développement - la solution logicielle

Le modèle proposé représente la base de la solution logicielle développée. Cette solution doit être utilisée pour l'évaluation et la prévision des performances du produit. Comme le montre le modèle, la solution est entièrement basée sur la méthodologie multi-agents. Ainsi, toute la modélisation est réalisée dans le logiciel AnyLogic basé sur des agents. Les informations nécessaires au fonctionnement du modèle sont définies dans le tableau Excel qui est importé dans la base de données AnyLogic. La base de données est mise à jour avant chaque simulation.

La structure du logiciel est basée sur le comportement des agents qui composent le modèle. Le modèle comprend trois types d'agents correspondant à la liaison FBS. Les agents de structure, de comportement et de fonction sont créés. Chaque agent représente l'élément de produit correspondant. Un type d'agent peut avoir autant d'agents individuels que nécessaire pour décomposer le produit. Des réseaux d'agents sont formés pour représenter les liens fonctionnels, comportementaux, structurels, fonction-comportemental et comportement-structurel. Les liens sont caractérisés avec seulement deux paramètres : la force (probabilité) et la sensibilité.

Tous les types d'agents partagent la même structure et ce sont les données qui les distinguent. En gardant à l'esprit que les solutions appliquent la simulation SIR modifiée, les états des agents sont définis en conséquence. Comme le montre le diagramme d'état de la figure 3.13, chaque agent peut se trouver dans

l'un des états suivants à un moment donné : sensible, propagation du problème, propagation de la solution et fini.

En raison de la communication constante entre eux, les agents détiennent les informations relatives à leur identifiant unique. Les réseaux sont décrits sous forme de collections afin de saisir leur force (probabilité) et leur sensibilité. Ainsi, pour chaque agent connecté, les informations sur son identifiant et son lien avec lui sont stockées. Toutes les caractéristiques du réseau sont représentées par une valeur flottante entre [0, 1]. Ces données sont utilisées pour la propagation aléatoire de problèmes et de solutions.

Comme indiqué précédemment, les facteurs de risque sont saisis sous forme de variables : Gravité de la valeur, Gravité des exigences, Gravité de la technologie et Gravité de la performance. Les variables ont une valeur qui appartient à [0, 1]. Elles sont initialisées au début de la simulation et évoluent au cours de son exécution.

Le fonctionnement des agents est décrit à l'aide de l'algorithme présenté dans la figure 3.14.

### **3.4.** Gestion des risques pour les produits en cours de développement - utilisation des solutions

La procédure d'évaluation des risques comprend l'identification, l'analyse et l'évaluation des risques. La cartographie de la solution à ces étapes est présentée dans la figure 3.17.

L'évaluation des risques est couverte par la solution développée et est effectuée manuellement. Elle est fortement basée sur la décomposition du produit (FBS). Le produit dans la thèse est constitué d'éléments de produit (fonctionnels, comportementaux et structurels) et des liens entre eux. Dans cette optique, l'utilisateur doit attribuer toutes les gravités de risque associées aux éléments du produit et décrire les liens entre eux en utilisant les forces et les sensibilités. Par conséquent, l'analyse des risques dans ce travail est effectuée de deux manières : explicitement et implicitement.

La partie explicite de l'analyse comprend la définition des sévérités des facteurs de risque. Dans cette étape, l'utilisateur doit juger le niveau actuel d'incertitude en matière de technologie, de ressources et de processus associé à chaque élément du produit.

Ce qui diffère dans cette approche du risque par rapport à celles couramment utilisées, c'est que l'utilisateur est invité à juger des incertitudes dans les facteurs qui le concernent directement. Le concepteur qui réalise une conception est généralement conscient si les exigences ne sont pas claires, si la technologie n'est pas stable ou si le processus de conception ne fonctionne pas comme il le devrait.

La partie implicite de l'évaluation diffère encore plus des procédures de risque courantes. Au cours de cette étape, l'utilisateur n'est pas invité à juger des risques. Il lui est demandé de fournir des informations relatives aux liens généraux entre les éléments du produit : à quel point deux éléments sont sensibles l'un par rapport à l'autre et quelle est la force de leur lien. Là encore, il s'agit des informations que le concepteur utilise quotidiennement.

Après analyse, une évaluation des risques est effectuée. En gardant à l'esprit la décomposition du produit, elle utilise comme entrée les degrés de gravité, de sensibilité et de probabilité obtenus à l'étape précédente et les déclencheurs de problèmes et de solutions. Cette étape est réalisée dans le simulateur proposé. Elle peut inclure une propagation unique ou une analyse de Monte Carlo pour le comportement de performance global. Son influence sur la prise de décision est illustrée dans la section suivante.

#### 3.5. Exemple de la solution proposée

Afin de mieux comprendre le fonctionnement, l'utilisation et le résultat des solutions, l'approche a été appliquée à un exemple de conception d'un sèche-cheveux. Le sèche-cheveux est décomposé comme dans (Hamraz et al., 2012). Les données manquantes ont été créées pour permettre la simulation. Le sèche-cheveux est un produit simple composé d'un ventilateur, d'un moteur, d'une unité de chauffage, d'une alimentation électrique, d'une unité de contrôle et d'un boîtier. Sa liste d'éléments fonctionnels, comportementaux et structurels est présentée dans le tableau 3.6. Les liens correspondants entre les éléments sont présentés sous la forme d'une matrice multi-domaines dans la figure 3.18. Les nœuds enfants pour chaque élément du produit sont représentés en lignes. Les parents des éléments de produit sont représentés en colonnes. En raison de la nature illustrative d'un exemple présenté, un problème simple a été étudié. Étant donné que pour les sèche-cheveux classiques, la technologie et les exigences sont considérées comme bien connues, leur gravité pour tous les éléments de produit est fixée à 1. Par conséquent, dans le tableau 3.6, seules les valeurs de gravité sont présentées.

Une simulation de modèle est présentée à la figure 3.19. Elle montre la propagation du problème apparu sur l'élément S0 et sa solution correspondante.

Une vue plus générale du comportement du produit peut être obtenue en utilisant la simulation de Monte Carlo. Comme aucune erreur souhaitée n'a été définie pour ce problème, le nombre d'exécutions est limité à 1000. Cette analyse peut donner des informations sur l'élément critique, les récurrences du problème, la valeur de risque la plus faible, mais aussi le test de différents scénarii.

La composante critique peut être déterminée sur la base de la plus forte récurrence du problème (figure 3.20a) ou sur la base de la plus faible performance (figure 3.20b). Pour l'exemple observé, la récurrence la plus élevée est obtenue dans 60 % des cas par F0 et dans 30 % des cas par S0. Dans le cas de la performance la plus faible, une analyse plus approfondie du produit est nécessaire puisque les valeurs les plus faibles ont été atteintes par F1, F3, S0 et B7 dans 10 à 30 % des cas.

La solution soutient l'analyse de différents scénarii afin d'avoir une vue sur les facteurs influents dans différentes conditions. Dans cet exemple, différents délais de solution, taux de propagation du problème et sensibilités ont été étudiés. Le délai de solution était de 40 ou 20 unités de temps après l'apparition du problème. Le problème a été étalé toutes les 3 ou 6 unités de temps. La sensibilité était soit 1 soit 0,1 pour toutes les connexions. Les scénarios et leurs résultats sont présentés dans le tableau 3.7.

Cet exemple illustratif a montré plusieurs possibilités d'analyse à l'aide d'une solution développée : la composante critique, la récurrence, les valeurs de performance, la sensibilité et l'influence du scénario peuvent être testées.

## **3.6.** Gestion des risques pour le produit en cours de développement - conclusion sur les travaux effectués

Compte tenu de tout ce qui précède, les contributions sont les suivantes :

- La solution présentée forme un modèle basé sur les facteurs (tâche, exigences et incertitude technologique) et sur le cadre FBS pour permettre la représentation et l'interaction des risques de performance
- La propagation des risques comprend deux flux : le problème et la solution représentent des changements dynamiques dans le produit. Avec la simulation SIR modifiée proposée, la solution permet de prédire et d'évaluer la performance d'un produit en temps utile.
- Différents facteurs de risque et leur influence peuvent être simulés en même temps.

- Sachant que la solution est stochastique, aucune connaissance ni aucun scénario n'est nécessaire pour l'identification des risques. Par conséquent, le modèle peut être utilisé pour préparer les informations de l'AMDE(C).
- Grâce à l'analyse de Monte Carlo, la solution logicielle devient un puissant outil d'aide à la décision.
- L'outil permet d'identifier les composants critiques, les récurrences, les itérations et les niveaux de performance.
- Différents modules d'un même produit peuvent être simulés et directement comparés en raison de la nature modulaire d'une solution.
- Aucune solution d'une telle exhaustivité n'a été identifiée dans la littérature.

## 4. Framework opérationnel et simulateur pour la gestion globale des risques dans le développement de produits

## 4.1. Gestion générale des risques dans le développement de produits : appel à l'action basé sur l'état de l'art

Dans les trois premières sections, trois études différentes sur la gestion des risques ont été menées. Elles ont toutes trois mis en évidence l'absence de lien entre les approches liées aux processus et aux produits. Ce problème a également été signalé dans la littérature par Eckert et al. (2015). Cooper (2003), dans sa critique de la pratique actuelle de la gestion des risques, a plaidé en faveur des liens entre les "mondes de la pensée". La principale question à laquelle il faut répondre est la suivante : comment traiter les interactions de risque pour permettre une vue globale du produit et du processus ?

La solution est divisée en deux parties : le modèle MBSE (ingénierie système dirigée par les modèles - voir 1 dans la figure 4.2) et les risques (voir 2 dans la figure 4.2). Sur la base de la littérature et des travaux réalisés pendant la thèse, on pense que l'ingénierie système peut fournir une description adéquate du comportement et que des approches standardisées des risques peuvent permettre de prendre en compte les risques individuels. Les risques capturés sont cartographiés en paramètres système (3 et 4 dans la figure 4.2) à partir desquels ils progressent dans le système en utilisant les modèles comportementaux. L'ingénierie système permet tous les processus liés au comportement, depuis le processus de développement (voir 5 dans la figure 4.2) jusqu'au produit (voir 6 dans la figure 4.2). Dans la thèse, ces processus comprennent les solutions de processus et de produits et leur connexion. L'idée est donc d'établir une distinction claire entre l'aspect comportemental du risque et le risque épistémique.

La principale flexibilité réside dans le fait que différentes approches peuvent traiter différents paramètres. Ainsi, la solution décomposée en une partie système et une partie approche du risque peut convenir à différents utilisateurs, scénarios et informations disponibles. Une attention particulière a été accordée à la connexion processus-produit (voir 7 dans la figure 4.2). Plutôt que d'être un modèle séparé, la connexion processus-produit préserve les deux modèles séparés et les fusionne en un seul. Le processus est décomposé en tâches, chacune elle ayant ses produits (8 dans la figure 4.2). Le produit est également décomposé (9 dans la figure 4.2). Tous les produits peuvent être mis en correspondance avec le processus et le produit (voir les points 8 et 9 de la figure 4.2). Cette connexion permet de "croiser" l'influence du processus au produit et vice versa. Comme l'indique la théorie de la conception, la tâche de conception définit clairement le travail effectué par un concepteur, mais a également son impact sur le produit. C'est le cœur de la connexion entre le processus et le produit. Les produits du processus sont assortis à l'élément de produit adéquat. Ainsi, l'influence du processus peut être définie pour chaque élément du produit (voir le point 10 de la figure 4.2). En réaction à cette influence, mais aussi pour

d'autres raisons, les produits sont formés. De même que ceux du processus, ils peuvent avoir un impact sur certaines tâches du processus (voir 11 dans la figure 4.2). De cette façon, sans modifier les solutions individuelles de processus et de produits, un modèle intégré de processus-produit est établi. Ses détails sont présentés dans la section suivante.

## 4.2. Gestion globale des risques dans le développement de produits - cadre proposé et le modèle

L'idée principale de cette solution globale de gestion des risques est basée sur les liens entre le processus et le produit. Ceci est illustré dans la figure 4.3.

Comme le montre la figure, le problème est décomposé en processus, produit et leurs connexions. Le processus et son produit considèrent tous deux des risques indépendants et dépendants. Les risques indépendants n'ont un impact direct que sur le processus ou le produit (voir 1 dans la figure 4.3). Au niveau du processus, ces risques comprennent les événements de risque individuels qui ont un impact sur les paramètres comportementaux. Les processus sont constitués d'activités. Les réseaux d'activités forment le comportement des processus. Bien que le comportement d'une activité et d'un produit (voir 2 dans la figure 4.3) soit représenté par des nœuds et des connexions entre eux, l'influence du risque ne se limite pas à son impact direct. Ainsi, en affectant un nœud, le risque peut se propager à travers d'autres nœuds en utilisant les connexions entre eux.

Chaque activité de conception définit un ou plusieurs éléments du produit (voir 3 dans la figure 4.3). Par conséquent, lorsque le risque a un impact sur une activité, son influence peut également affecter un élément de produit (voir le point 4 de la figure 4.3). Une tâche de conception mal exécutée peut entraîner des problèmes de fonctionnement du produit. De même, lorsque l'élément de produit est affecté, l'activité correspondante est également affectée. Si l'on constate que la technologie choisie ne fonctionne pas comme souhaité, un effort supplémentaire du concepteur est nécessaire pour résoudre le problème. Le risque lié à l'activité est donc affecté.

Les risques liés aux résultats du processus et aux performances du produit (voir le point 5 de la figure 4.3) peuvent simplement sembler indépendants. Grâce à l'interconnexion au sein et entre le processus et le produit, le risque qui en résulte est plus un état stable d'un système fortement connecté.

Le cadre proposé utilise un cadre FBS modifié pour cartographier la gestion des risques liés aux produits et aux processus. La figure 4.5 illustre ce cadre.

La représentation des processus est basée sur les transitions du FBS. Afin de "déplacer" un produit d'un aspect (F, B ou S) à l'autre, les transitions doivent être exécutées. La seule façon d'effectuer la transition est de réaliser des tâches de conception adéquates. Ainsi, chaque activité du processus peut être liée à une transition et à un ou plusieurs éléments du produit. Alors que toutes les activités sont directement liées à leur(s) transition(s), certaines activités ne sont qu'indirectement liées à des éléments de produit. L'élément du produit subit des changements avec chaque fonction exécutée qui lui est directement ou indirectement liée. Cependant, on suppose que le risque se propage une fois que toute la transition est effectuée.

Il a déjà été précisé que l'activité doit être mise en correspondance avec les transitions dans le modèle FBS modifié. Les transitions représentent la transformation d'un produit d'un état à l'autre. La transformation est effectuée en utilisant la tâche et l'acteur associé. Les transitions sont décomposées selon Gero (1990) et Cascini et al. (2013). Selon cette classification, les transformations de conception et, par conséquent, le processus de développement peuvent être représentés à l'aide de 4 types d'activités

: analyse, synthèse, choix et évaluation. Leur définition pour la nécessité de ce travail est présentée dans le tableau 4.1.

## **4.3.** Gestion globale des risques pour le développement de produits - la solution logicielle

La solution proposée combine des modèles déjà développés dans l'ensemble. Ainsi, en termes d'organisation générale du logiciel, il s'agit d'une combinaison de modèles développés antérieurement (figure 4.7). L'outil UnBBayes est utilisé pour modéliser les événements externes et leurs réseaux (réseaux bayésiens). Le modèle principal est développé dans AnyLogic et toutes les informations nécessaires sont stockées dans Excel. Comme les modèles indépendants de processus et de produits ont été développés en utilisant la même technologie et le même logiciel, seule une adaptation des deux a été nécessaire. Les deux solutions ont été fusionnées en une seule.

La structure complète du modèle est présentée dans la figure 4.8. Elle se compose des classes présentées dans les modèles de processus et de produits et de leurs connexions, paramètres et méthodes.

L'agent « activité » est le seul agent de processus sur lequel les changements ont été appliqués. Le nouveau diagramme d'états de cet agent est présenté à la figure 4.9. Le diagramme d'états et la figure sont utilisés pour illustrer le nouveau comportement de l'activité dans le contexte de la gestion globale des risques.

Tout comme le processus, le modèle produit a été modifié pour s'adapter à la gestion globale des risques. Étant donné que le modèle de processus individuel traite de certains aspects du processus, dans le modèle adapté, ces fonctionnalités ont été supprimées puisqu'elles sont prises en compte par l'agent d'activité. Le modèle de produit mis à jour est présenté à la figure 4.10 à l'aide d'un diagramme d'état des éléments de produit.

## 4.4. Gestion globale des risques dans le développement de produits - utilisation des solutions

L'évaluation globale des risques combine les étapes de solutions individuelles de gestion des risques liés aux processus et aux produits (figure 4.12). De nouvelles étapes traitant de l'interaction entre le processus et le produit sont élaborées plus en détail.

La nouvelle étape comprend l'identification des risques liés aux processus et aux produits. En utilisant les données du registre des risques et leur expérience, les analystes des risques recherchent les liens entre le processus et le produit et vice versa. Lors de cette étape, l'utilisateur doit être conscient que certains facteurs de risque liés au processus et au produit ont déjà été identifiés dans la littérature et mis en œuvre dans la solution. Ces facteurs comprennent : l'influence de la valeur sur l'incertitude et la compétence des performances du produit, la communication, l'organisation et l'impact de la qualité du fournisseur sur l'incertitude technologique. Si d'autres liens particuliers entre le processus et le produit sont constatés dans le registre des risques, ils doivent être marqués pour l'analyse des risques du processus-produit.

Une fois que l'analyse des risques liés aux processus et aux produits individuels est effectuée, une analyse intégrée processus-produit est réalisée. Cela comprend la formulation de règles et/ou de conditions qui définissent l'interaction entre le processus et le produit. Certaines règles ont déjà été mises en œuvre. L'influence de l'activité sur l'élément produit a été définie en fonction du type d'activité. Si une autre règle existe dans le développement réel du produit, elle doit être ajoutée dans cette phase de l'analyse de risque.

Une fois l'analyse des risques terminée, l'évaluation des risques est effectuée automatiquement dans le logiciel développé. Le logiciel permet de calculer et de prédire les risques et les résultats sont axés à la fois sur le processus et sur le produit. Ainsi, le temps, le coût et la valeur globale de l'activité sont calculés. Au niveau du produit, le risque de performance est déterminé pour chaque élément du produit. La solution compte également le nombre d'itérations nécessaires au niveau du processus et du produit, de sorte que la planification du processus peut être adaptée sur la base des informations acquises.

#### 4.5. Exemple illustratif

L'exemple comprend les 15 premières tâches présentées dans la section 2. Par conséquent, toutes les données pertinentes pour le processus sont les mêmes que dans l'exemple de ce chapitre. On considère que le but des tâches est de choisir les matériaux pour tous les composants du sèche-cheveux : ventilateur, moteur, unité de chauffage, boîtier, puissance et contrôle. Comme dans le chapitre 3, le produit est considéré comme bien connu et, par conséquent, le lien entre le processus et le produit est établi directement au niveau de la tâche et de la structure. Pour le développement de nouveaux produits, le processus peut être relié au produit au niveau fonctionnel ou comportemental. Le tableau 4.2 présente le lien entre le processus et le produit pour le cas observé. Pour que la simulation des risques puisse être réalisée, il faut déterminer les besoins initiaux et les informations technologiques. L'objectif de cette simulation n'est pas de choisir entre différentes technologies pendant la simulation, mais de représenter l'influence globale sur le risque. Par conséquent, si le choix entre différentes technologies est nécessaire, il peut être effectué en analysant les résultats de simulations séparées. Le tableau 4.3 présente les exigences initiales et les informations sur les technologies.

Le tableau 4.3 présente deux options pour le risque technologique et une pour l'exigence. Les différentes options en matière de risque technologique ont pour but de simuler différents choix. Deux groupes d'expériences sont menés. Dans le premier, le risque technologique d'une unité de chauffage est initialement fixé à 0,92 (S7 T=0,92). Le second groupe teste différents modules technologiques avec un risque technologique initial de 0,733 (S7 T=0,733).

La simulation montre le coût, le temps, la valeur et le nombre d'itérations au niveau du processus. Et la performance du produit. Les résultats montrent que différentes options de contrôle peuvent améliorer les performances et réduire le nombre d'itérations. Dans le scénario T=0,92, il n'y a pas de problème, même au niveau fonctionnel. Dans le deuxième scénario, les fonctions entrent dans leur boucle comme dans les cas précédents. Cela peut signifier qu'une régulation de l'influence du processus peut être une partie de la solution. La deuxième partie pourrait être une décomposition fonctionnelle pour éviter de nombreuses relations entre les éléments du produit.

#### 4.6. Conclusion

En général, les contributions aux solutions peuvent être résumées de la manière suivante :

- La solution fournit une vue complète du processus et du produit de la gestion des risques.
- Elle permet de quantifier les interactions entre les risques de la base vers le sommet.
- Elle soutient les règles qualitatives et quantitatives qui permettent de déterminer lesquelles peuvent être utilisées dans différents de développement et sur la base de différentes sources de données.
- Elle est flexible pour l'ajout de nouvelles règles et relations.
- Il permet une gestion des risques qui suit les principaux processus de développement et leurs produits.

#### 5. Discussion et conclusion

Trois limitations potentielles liées à la solution de gestion des risques développée ont été identifiées :

- L'applicabilité de la solution à différents processus de développement,
- Rassemblement des informations pertinentes nécessaires à la modélisation des risques,
- Adoption de la solution par l'utilisateur.

Les premières mesures ont été prises pour surmonter ces problèmes.

Les solutions proposées ont été illustrées par le développement d'un appareil ménager du quotidien (sèche-cheveux). Si cet exemple peut être facilement mis en correspondance avec différents domaines d'ingénierie, la question est de savoir s'il peut convenir à un produit au sens large du terme. La solution développée a été appliquée à un autre exemple - la thèse de doctorat a été observée comme un processus de développement. Cette application montre le potentiel d'une solution de gestion des risques à être utilisée pour un large ensemble de développements.

Le nouvel exemple a montré comment l'approche développée peut être appliquée pour recueillir des informations lorsqu'un expert en processus modélisé les informations est également un expert en processus. Cependant, dans la majorité des cas, la solution serait appliquée par des utilisateurs qui ne sont pas nécessairement familiers avec la modélisation. Une enquête a été créée et testée sur un petit groupe d'experts afin de montrer comment sonder les experts pour les guider dans la création de la FCM.

Afin de rapprocher les idées principales de la solution proposée des utilisateurs, un serious game a été conçu. Actuellement, ce serious game se concentre principalement sur le produit et ses risques. Le jeu inclut également la notion de propagation des problèmes et des solutions. Il est prévu d'étendre le jeu afin d'inclure davantage d'éléments de processus présents dans la solution réelle.

À travers les exemples présentés dans la section de la thèse et ceux qui sont présentés ici, on peut affirmer que la solution développée peut répondre aux défis du développement de produits. Elle peut prendre en compte divers processus de développement et de produits. Des enquêtes guidées approfondies et des jeux sérieux peuvent aider l'utilisateur dans le développement de son modèle, avant d'effectuer une estimation des risques basée sur la simulation. L'ensemble du processus peut aider les utilisateurs à reconnaître le comportement du système et à mieux comprendre leurs processus et produits. Enfin, le principal atout de la solution est sa flexibilité qui permet aux utilisateurs de passer d'une gestion des risques centrée sur les experts à une gestion des risques basée sur les données.
**English Version** 

## Chapter 1: Introduction and overview

#### Abstract

This chapter introduces the main topics of the thesis. It covers the first phase of the research and details the conducted study of risk management tendencies in engineering design. The study indicates the need for a joint approach for the product and its development process. It also emphasizes the gap between the general risk approaches and those that are tailored for specific engineering problem. Consequently, it provides the outline of the thesis. The main goal of the thesis is set as the project and the product interaction representation for development process. The main ideas include systemic and bottom-up representation of risk, dynamic evaluation and flexible view on risk. The differentiation between the behaviour of the project and external events is set. Having in mind that the study has also indicated the need for the tool and statistical approaches to deal with the risk, it has been decided to develop a solution in the form of a simulator. The research methodology that led to the desired solution is represented as a 5-step process including the conducted literature review, project-related solution, product-related solution, general solution and application through the study of a case. The chapter also emphasizes the main contributions and limitations of the performed work and it is finished with the organization of the thesis.

## 1. Problem definition

Managing risks during the product development requires keeping an eye on numerous facets. From project to product aspects, risk management should cover all and provide adequate input for decision-making. With the history of over 55 years (Dionne, 2013), one may assume that this well-established process can fulfil these high demands.

Although covered by the appropriate standard (*Risk Management – Risk Assessment Techniques Management Du Risque – Techniques d'appréciation Du Risque*, 2019), the problems and surprises supposedly caused by the unexpected events are not as rare as it might be expected. In that sense, two famous projects can be called to mind – Takata and Airbus A380. In Takata airbag problem (Tabuchi, 2016) one unstable chemical, defective manufacturing practice and flawed quality control provoked a recall of 41.6 million vehicles in U. S. only (Consumer Reports, 2019). In the case of Airbus A380 saga, the length of installation cables led to the delay of this complex project. Organizational issues, communication problems between the two subsidiaries developing the plane and the lack of flexibility caused the accumulation of issues that were identified late in the assembly phase. Precisely, the problem has been detected when the plane couldn't be assembled due to the short cables. This late acknowledge caused painful shock for the company drawing the image loss, together with the time and money. Having in mind the reputation of the companies facing the described problems, undoubtedly the proven risk management practices have been used during these projects. Hence, it is necessary to question what these fails are telling about the current risk management practices.

The two main observations can be made based on these projects. Firstly, the risks are not observed in a holistic manner. Risk related to development process and product risks are dependent on each other. As seen in the cases of both Airbus A380 and Takata, even though the problem in its final form can be represented in the product, the origin can be related to project itself. In case of Airbus, the main reason for the short cables is not a technical issue, but the lack of communication and coordination between the development departments. Although for Takata some may say that the origin of the problem is unstable chemical, it shouldn't be forgotten that this information has slipped through the development process and quality control. Hence, the development process clearly influences the product. But the similar observations can be made in case of product-to-project influence. Due to the failure of the final product, the project required additional time and resources to answer to the new situation. Risk management practice is not often taking these interactions into account which leads to the problem like the ones of Takata and Airbus. Hence, successful development project requires successful project and product aspects. In the same way, risk management should focus on both aspects and their influences. This leads to the second observation. As stated for the Airbus A380, "It doesn't matter if it's [cable] short by 40 millimetres or 40 meters, ... But after a while it becomes a cumulative problem." The risk grows through the project. Like the butterfly causing the wind on the other side of the planet<sup>1</sup>, initially small problem can shake the foundation of the project. And this is what happened to Airbus A380. The bigger the project, more interactions, propagations and places for the risk to grow. Hence, the risk management should be able to capture the propagation of the risk and its growth in the later stages.

<sup>&</sup>lt;sup>1</sup> Chinese proverb says: "The flapping of the wings of a butterfly can be felt on the other side of the world."

After analysing the two projects, the notion of "unexpected events" from the beginning of this chapter can be viewed in a different perspective. Are those "surprise risks" a consequence of a risk management? The answer is yes and no. While certain events surely can't be predicted (natural catastrophes, epidemics, etc), it would be wrong to say that the interactions in the projects can't be taken into account. In that sense, interactions and propagation of risk through the development process and product can be considered as a manner to get to know ourselves. The other events that can't be predicted explicitly are the enemy that we're aiming to get to know. The vast majority of risk approaches focuses on this enemy. Collecting statistic on different risk events, analysing and evaluating them represents the base for their risk management. In those cases, the whole focus is given to the enemy leaving little to no knowledge about the development itself. The answer to the question why those methods are giving just partially proper results, can be searched in 2500-year-old literature.

Without going too deep into relations between the war and business (McCormick, 2001; Niou & Ordenshook, 1994), Sun Tzu's "Art of war" (Tzu, 2004) may explain what is necessary to conquer the risks. Focusing on the winning the battle, he states:

"If you know the enemy and know yourself, you need not fear the result of a hundred battles. If you know yourself but not the enemy, for every victory gained you will also suffer a defeat. If you know neither the enemy nor yourself, you will succumb in every battle."

The current risk approaches are so focusing on the enemy (unpredictable events), that our own behaviour is left untreated. Hence, no matter how well we study the enemy, the failure is just waiting around the corner. The solution for better risk management may be in enforcing our development process and product knowledge, rather than focusing on getting to know the unknown. Consequently, the goal of the thesis is to develop a comprehensive risk management solution that makes the clear boundary between the external events and development process and product behaviour represented through the interactions and propagations.

## 1.1. Scientific issue

Summarizing the observations from the previous section, the scientific question can be defined as follows:

## How to <u>assess mutual interactions</u> between <u>product's characteristics</u> and their <u>development risks</u> to enable <u>decision-making and dynamic monitoring</u>?

This global question can be further decomposed into following sub-questions using the key word from the main one:

- 1. Product's characteristics
  - 1.1. What is the appropriate risk or risks to represent the product?
  - 1.2. What is the proper decomposition of the product and how to represent the emergence form one product level to another?
  - 1.3. How to represent and model risk behavior including the interactions between product elements and the propagation form one element to another?
- 2. Development risks
  - 2.1. What is the appropriate risk or risks to represent the development process?
  - 2.2. What is the appropriate model of the development process to enable adequate risk management?

- 2.3. How to represent risk behavior to include interactions and propagation of risks within the development process?
- 3. Mutual interactions
  - 3.1. What is the connection between the development process and the product that enables risk management?
  - 3.2. How to model causal relations between the project and the product?
- 4. Decision making and dynamic monitoring
  - 4.1. How to enable dynamic assessment of risks?
  - 4.2. How to tailor-made risk information for the different decision makers (stakeholders)?
- 5. Assess
  - 5.1. How to identify, analyze and evaluate risk for the corresponding problem?
  - 5.2. What is the appropriate way to represent the results of the assessment?

As it can be seen from the questions, the scientific issue can be divided into three main sections: product-, project- and project-and-product-related risk management. Although project and product require separate analysis, their representation should bear in mind the integration between the two.

Question 1 focuses on the risk management of the product. Although subject of many product-related or failure-oriented risk management approaches, in this thesis product needs to be observed with the influence of the underlying development process. With this in mind, it is necessary to define all the observed risks, granulation and risk behavior.

Similarly to the first question, question 2 aims at positioning project risks and their interactions but also at enabling connections with the product. Based on the project risk management approaches, the question aims at emphasizing the necessary changes to suit the need of the thesis.

Question 3 represents the base of the connections between a development process and a product. Consequently, it can be seen as the root of the thesis upon which all the project and product models are built. Chronologically, it is in this question where major assumptions are made. Those assumptions directly influence the global project-product risk management approach, but also the development of the project and product modules separately.

Question 4 has a goal to emphasize that the desired output of the thesis is to be used as a support for decision-making. As seen in the case of Airbus, the flexibility of the company is considered crucial in big development projects. The purpose is therefore to provide a flexible approach with the potential of taking into account changes that that occur during the project while at the same time tailoring risk representation to the various stakeholders involved in the development process. The two questions are in accordance with the previously mentioned.

Lastly, the thesis boundary regarding risk management is set in the fifth question. The solution is to cover risk assessment process, meaning that for individual project and product solutions, as well as for global project-product solution, risk identification, analysis and evaluation need to be defined. This question also includes the adequate representation of the final risks. The optimization of risk is considered out of the scope.

## 1.2. Major ideas included

Several ideas are driving the thesis. Certain can be deducted from the scientific questions, while others are initial assumptions that need to be defined separately. They are all listed in this section.

## Project and product are considered as systems.

The thesis is strongly based on the ideas of General Systems Theory. Hence, project and product are considered in its "wholeness" and can't be understood through the investigation of the individual elements (Von Bertalanffy, 1968). Their behaviour is considered complex in a way that "the whole is more than sum of its parts" as written by Aristotle and used in the context of system behaviour by Grabowski & Strzalka (2008).

## Project, development process embraced by design.

Design stage is considered crucial in product development. At the end of the conceptual design, 75% of product's cost have already been committed (Ullman, 2010). Also, at this stage risk is considered as highest due to the lack of information (T.R. Browning et al., 2002). Hence, suiting the risk management solution to the weakest development step has been set as a priority. This, however, doesn't limit the usage in other development phases.

## Project adds value to the product.

Being a direct result of the development project, the product is influenced by the project behaviour. Projects that diverge in their structure, have different stakeholders or are performed in disparate ways will not produce the same final product. Hence, the relationship between project and the product is defined as a "value chain" i.e. collection of activities leading to a product of development (Porter, 1985).

## Development process requires iterations and modifications.

The development process is not a one-shot activity that aims straight at the target and creates the product that the customer needs. It is more tedious process of trial and error which results in the desired product. Hence, not taking into account the iterative nature of the process and the need for changes or modifications on both product and project level is considered as big approximation. In this thesis, iterations and modification take part in risk management.

## Project and product are susceptible to uncertainty.

Development project and its product depend on many factors. Final results strongly depend on actors involved, their skills and performance, requirements or technology used, to name a few. And all these elements are uncertain, either due to the changes that may arise or due to our knowledge (or better to say lack of it) related to them. Bearing this in mind, the results of the risk management represent a variation from the planned result.

## Risk has many faces.

As it has been stated in the beginning of this thesis, the tool to fight the risk may be in getting to know ourselves. With that stated, the risk is observed as external and internal. Internal risk includes the risk itself but also its interactions and propagations through the development system and the product. External covers events coming outside of the observed systems. This leads to the clear distinction between "myself" and the "enemy". It shouldn't be forgotten, however, that what is considered external to one can be internal to the other. Hence, in order to see the real face of the risk, the boundaries of the observed systems should be crystal clear.

## Risk management is to support the development.

Risk management is a process. Process related to another process - development process. And, interactions between the processes are sometimes vague and time consuming. Especially, when it requires to take a step back from design to analyse risk for which appropriate data may or may not have been available. Hence, risk is often everything but effortless. Certain authors have even conducted studies explaining all the issues facing practitioners in risk management (see Cooper, 2003; Schindel, 2010). Hence, in this thesis, the goal is to create a solution that can support the development work. The solution that can be carried on as the development process progresses.

## "Simplicity is the ultimate sophistication." (Attributed to Leonardo da Vinci)

Related to the previous remark, the risk management solutions are often distant from the work that is performed. Sometimes they require general overview of the project and that knowledge is not easy to gain. Also, the question is: who is to attain this knowledge? Hence, the goal is to create a bottom-up approach which the actors can use with their hands on the project.

#### "He will win who knows when to fight and when not to fight." (Tzu, 2004)

In development project, the proper information at the proper time is crucial. In the Airbus project, small errors led to the big fail since they hadn't been recognized on time. Hence, having the possibility to evaluate risk at any time in the project is important. Being able to ask and to get the answer to the "what if" is the goal of the risk management proposed in this thesis.

#### Risk management solution to fit different processes and products.

Lastly, the risk management solution is not area-, product- or project-specific. The goal has been to provide a general and global solution that can be adapted to different processes and products.

## 2. Risk management in engineering literature and the action needed

So far the need for the integrated solution has been identified based on the situation in engineering practice. The identification of scientific gap would however be incomplete without adequate literature analysis. Hence, the study on risk management tendencies in engineering literature has been conducted. The goal has been to perform unbiased article identification and to determine the following:

- 1. What is the trend of interest in risk management in engineering area?
- 2. Is there a need for general approaches?
- 3. How is risk defined in engineering literature?
- 4. How risk approaches support engineering?
- 5. What is the maturity of the available solutions?
- 6. What is the most addressed risk management phase?
- 7. What is the correlation between the different risk aspects?

The study has included identification of articles using keywords in the title in 4 scientific databases: SpringerLink, Science Direct, Taylor & Francis Online and Wiley Online Library. The key words that have been used are "risk" and "design". More on the choice of keywords, the reader can find under the subsection 2.1. Bearing in mind the long history or risk management, the goal hasn't been to create exhaustive analysis on risk management approaches but rather to see recent trends, attitude towards risk management and identify the current scientific gaps. More about risk approaches can be find in the corresponding risk standards (ISO 31000 and ISO 31010) and in Chapter 2 and Chapter 3 of the thesis. With this in mind, firstly, the search has been limited to period between 1998 and 2018. The search is limited to 2018 since the analysis has been performed in the first year of the thesis to investigate adequacy of the research subject. Secondly, the search has also been limited to engineering articles. Hence, whenever it was possible the filter was turned on to indicate the research area. In case the filter wasn't available, the manual selections of the articles based on the subject was performed. Lastly, articles from the supply chain areas have been excluded from the analysis since this area can be considered as a complementary area to engineering and its vast resources usually form a community on their own.

## 2.1. Assumptions of the study

As stated earlier, to perform the trend analysis of risk management in engineering several assumptions regarding the choice of keywords. These assumptions are listed in the following subsections.

#### 2.1.1.On risk

In the study, the keyword "risk" has been used to consider broad notion from management to the lexical meaning of the term. ISO defines risk as an effect of uncertainty on objectives (*31000: Risk Management — Principles and Guidelines*, 2009). Although mainly described as an effect, the same standard emphasizes that risk is usually represented as a combination of the consequence of the event and its likelihood. Hence, one may conclude that risk is a value that represents the effect of uncertainty calculated as a combination of consequence and likelihood. While this is true, in certain cases variations exist from this initial definition. Firstly, in a common language and literature risk is often considered as "danger". Secondly, the term "risk" is sometimes represented by or used together with other terms such as: uncertainty, probability, robustness, reliability. Thunnissen (2003) observes that risk represents outcomes occurring with known probabilities, while uncertainty is characterized by unknown outcomes or probabilities. Van Bossuyt et al. (2013) establish a clear connection between the risk and robustness and reliability. Hence, the study has a goal to investigate the attitude towards these two observations. Firstly to see if risk is observed as hazard (safety view of risk) or more general (non-safety view of risk). Secondly to investigate if risk is defined as in ISO standard or it comprises other notions like uncertainty, probability, robustness, reliability.

## 2.1.2. On project and risk management

In order to address different phases of risk management and their representation in engineering literature, those phases need to be defined. Previously, it's been mentioned that risk represent a process that is also part of project management process. Hence, depending on the literature source risk management phases are defined differently. PMBOK (Project Management Institute, 2013) includes planning of risk management, identification of risk, qualitative risk analysis, quantitative risk analysis, planning of risk responses and control of risks as major phases of risk management. ISO 31000 on the other hand comprises communication and consultation, establishment of the context, risk assessment, risk treatment and monitoring and review. Here, identification, analysis and evaluation are included in risk assessment. In order to avoid any ambiguity, ISO standard is used to define risk management phases in this study and throughout the thesis.

## 2.1.3.On design

As explained earlier, in this thesis, design is considered as the major link between project, product and risk. Being integral stage of a development project and maybe the most influential phase of the product

life cycle (due to the definition of the 75% of overall cost), "design" is also one keyword in the study. Also, "design" can signify the whole development process in certain cases. Hence, by using it as a keyword product- and project- focused literature can be identified. Articles covering both product and project aspects are taken into account as well.

#### 2.2. Obtained results

220 articles have been identified based on the described approach. They have been stored in the online Zotero library. All the identified articles can be accessed through the following link: <a href="https://www.zotero.org/groups/2233109/riskdesigntendenciesinengineeringliterature">https://www.zotero.org/groups/2233109/riskdesigntendenciesinengineeringliterature</a>. Although one may argue about the number of articles needed for the analysis, it should be noted that this is not an exhaustive work. On the other hand, the main goal has been to provide objective and unbiased identification of articles. That's been done as described earlier. Hence, it is assumed that this sample of articles can illustrate major trends in engineering literature towards risk management. In the reminder of this subsection, the main observations are presented.

#### Question 1. What is the trend of interest in risk management in engineering area?

Despite the long tradition, risk management area is far from reaching its limits. Based on the publication year of the identified articles, the interest in this area is here and growing. The number of publications per year is presented in Figure 1.1-1. As it can be seen, the interest is rising almost exclusively during the past years. During most of the years (with the exceptions of 1999, 2003, 2009, 2010, 2015) the number of publications increases year over year. Although, this study is limited in number, the perceived trend implies that the risk management area is of interest for engineers. Also, it suggests that it becomes even more actual in the modern circumstances. Hence, it may be concluded that studying risk for engineering is worth the interest.

#### Question 2. Is there a need for general approaches?

Risk management approaches are already covered and explained in ISO 31010. For this reason, it is interesting to see if the authors are still working on new solutions that can be applied in different areas of engineering or even apart from engineering. If yes, this may indicate that the risk management area is still to be developed beyond the mentioned standards. Also, this would imply there is still a need for general solutions based on the current experience, state of science and practice. To investigate this trend, rather simple analysis has been conducted. For any identified article the area of research has been determined and the number of articles in each area has been plotted in Figure 1.1-2. As it can be seen, the biggest number of identified articles belongs to the general design. This can be partially explained due to the good representation of the design community with the keyword "design" used to identify the articles. On the other hand, it means that there is still a need for general risk management solutions in design. Hence, it can be argued that the current risk management standards together with the project management literature do not fully cover the demand. In terms of this thesis, it shows that the scientific gap is there and requires further investigation to give detailed information about the needs. This detailed analysis is covered in question 7, but also in the separate analysis of general approaches in subsection 2.3. This study has also identified interest in risk management for the construction area. This is no surprise since numerous projects are performed in this field and dealing with risk is part of their everyday tasks. Third and fourth biggest fields are water research and manufacturing, respectively.

## Question 3. How is risk defined in the engineering literature?

This question focuses on the definition of risk and its differentiation between safety and non-safety on one hand, and its usage with other terms such as uncertainty, probability, robustness and reliability, on the other. To track this information, for every identified article it has been determined whether risk is

observed purely from the safety perspective or not. Depending on the categorization, the "orientation to safety" has been set to "yes" if the article is safety-oriented and to "no" if it isn't. Similarly, if in the article risk is used with at least one of the other terms (uncertainty, probability, robustness or reliability), "joint risk terminology" has been set to "yes". Otherwise, it's been set to "no". The results can be summarized as follows.



Figure 1.1 Study on risk management in engineering - the obtained results

First analysis has been made for safety and non-safety. To distinguish between these two categories, the source of risk, events and effect have been studied. Based on the focus, the article has been categorized into safety or non-safety. As an example, articles that are observing different sort or risk events and not just those dealing with hazards would be categorized as non-safety. Hence, non-safety category observes risks in a more global way. It includes hazards but it is not limited to them. Finally, 101 non-safety and 119 safety articles have been identified. Hence, despite the general definition of risk in ISO 31000, the risk is still observed largely as hazard. This is no surprise, when considering the

consequences. Non-treated hazard in any area can have more severe consequences than the missed opportunity. It is interesting to deeper investigate this distinction between safety and non-safety. Based on their use, the identified solutions can be categorized as optimization, decision-making, solution of particular problem, study and risk tool design. In most of the use categories risk is equally present in the safety and non-safety manner. However, in the case of optimization two thirds of identified articles are safety-focused, comparing to one third of non-safety. One typical examples of the safety-oriented article from this category deals with the fire scenarios in the floor design. Hence, it is clear that great number of optimization articles are not focus on risk management in the standardized term. They are more likely to deal with the detailed model of the problem on which they will calculate risks in the form they need for this particular case. This opens the question whether these approaches really belong to the risk management in a way it is expected. Their main focus is on the modelling, hence they deal with the problem of the particular area and the results of the model are named as risks. Maybe, a clear terminology distinction should be made for different areas where instead of calling all the problems risk, to use the particular failure of interests like fire hazard, assemblability, flood probability, etc. On the other hand, this discrepancy between safety and non-safety approaches may call for the joint approach of the two.

Second analysis is closely related to the first one. 60 articles out of 220 consider risk with one of the following terms: uncertainty, probability, reliability or robustness. The question that arises is whether these one third of articles are using good terminology to describe their problem or not. The information about the scope of these articles are usually better described using one of those joint terms then with the term "risk". Risk represents the general notion, implying the effect of certain events while in joint terminology the "effect" can actually be the calculation of uncertainties. Without going into deeper consideration how one should address the risk and whether this term should be used at all, it is clear that the notion of risk changes its form easily. The risk joint terminology compared to different use cases is shown in Figure 1.1-3. As it can be seen, different notions of risk are almost equally present across different groups. Hence, it may be concluded that the proper description of the problem is crucial. Clear recommendation for the definition of different terms need to be determined for the scientific community and propagated to the engineering practice to avoid the confusion and conflicts.

#### Question 4. How risk approaches support engineering?

To determine the contribution of the developed solutions to engineering, the usage has been tracked. For each article the type of use of the described results have been categorized in one of the previously described categories: optimization, decision-making, solving of particular problem, study or tool design. Optimization solutions represent solutions that don't require any form of intervention to perform decision making. Decision-making solutions, on the other hand, provide information for risk managers. Similar can be said for the solutions focusing on the particular problem, but those solutions, as their name states, are bounded by the problem they're solving. Hence, contrary to the general decision making, they can be applied only on the described case. Studies provide insights about risk management in different areas. Risk tool design articles are improving or adapting known risk management approaches.

The distribution of different use cases is shown in Figure 1.1-4. As it can be seen, 74% of all the articles are asking for decision-making solution through optimization, general decision-making or particular one. This implies, that the community needs solutions to treat the risk. However, it shouldn't be neglected that 15% and 34% of articles belong to optimization and particular-problem solvers. This means, that potentially almost 50% of identified articles have in some form problematic definition of risk and usage in the standard risk management sense. One quarter of solutions belongs to the general

decision-making, implying the need for general solutions as well. Studies take 20% of all the solution. This may be explained with the need for the structuration or guidelines in this vast and diversified area.

#### Question 5. What is the maturity of the developed solutions?

To track the time until the potential automation of risk management process, a maturity of the solutions has been determined. All the articles have been divided into four categories: study, framework, methodology and tool. The results are presented in Figure 1.1-5. Most of the solutions are developed in the form of tools (56%). This can be interpreted in two ways. The engineering area have the need for the adequate tools. In other words, current approaches either need adaptation or they don't cover the current requirements. On the other hand, this number of articles directly implies that if there is a need for tools, the community is working on that. The engagement in this sense is clear since the tool development takes more than the half of all identified articles. However, the question that once again needs to be asked here is the influence of the optimization, particular solutions and joint risk definition. This will be covered in more detail in question 7.

#### Question 6. What is the most addressed risk management phase?

The categories for risk management phase have been determined using ISO 31000 and they include: communication and consultation, risk assessment, risk treatment and monitoring and review. Risk assessment has been further defined into risk identification, analysis and evaluation. This has been done due to the fact that certain articles can cover all of the assessment steps, while other are focusing on one of them. In case that the article addresses more than one step of the assessment, the whole process has been selected. The last categories are "all" and "none" determined for the articles that are either taking all risk phases into account or not referring to any of the them in particular. The results of the analysis are shown in Figure 1.1-6. There is no surprise to see 40% of articles belonging to the "none" category. This number is in great majority consisted of articles dealing with particular problems. Since they have little or no relation with risk management, they don't address any phase. Apart from these, 15% of solutions are optimization oriented and address only the evaluation of the assessment phase. This implies that the risk-orientation is presented in less than 50% of papers with the keyword "risk" in the title! Focusing on those articles, it is interesting to notice that 25% of all articles address the assessment phase. Hence, the biggest efforts in the community are made to provide solutions that will cover identification, analysis and evaluation of risks. Hence, it may indicate the possible direction for the thesis.

#### Question 7. What is the link between the different aspects?

Having an individual analysis is useful, but it can't determine relationships between different aspects. For example, it can't show if the joint risk terminology is more related to optimization and solutions of particular problems. To answer this and other questions of relations between different aspects, Multiple Correspondence Analysis (MCA) has been conducted.

Based on Abdi & Valentin (2007), MCA is a method that enables analysis of relationships patterns between a set of observations described by nominal variables. Nominal variable is consisted of set of levels. Each observation can be in one level per variable. Six nominal variables were selected to analyze the identified articles: use of solution, maturity, generality, joint terminology, safety and risk phase. The levels of each variable are shown in Table 1.1.

$oldsymbol{U}$ - Use		<b>M</b> - Maturity		<b>G</b> - General		<b>T</b> - Joint		S - Safety		<b>R</b> - Risk phase	
						term	inology				
0	Optimization	S	Study	Y	Yes	Y	Yes	Y	Yes	Cm	Communication
D	Decision making	F	Framework	Ν	No	Ν	No	Ν	No	Ct	Context
Р	Problem solving	Μ	Methodology							Ι	Identification
S	Study	Т	Tool							Α	Analysis
T	Tool design									Е	Evaluation
										Т	Treatment
										Μ	Monitoring
										At	Assessment
										All	All
										Ν	None

Table 1.1 MCA for study on risk in engineering: selected variables and their levels

Each identified article can be in one level per variable. As one can notice, all the variables and levels represent categories that have previously been used for analysis. Only one change has been made in order to reduce complexity of the problem. Instead of observing all the articles depending on their fields of research, the variable "general" has been made. This variable indicates whether article is general in nature or it belongs to any engineering field (construction, mechanical engineering, to name a few). Hence, if the article is general, it will be categorized as "G-Y", where "G" indicates the name of the variable ("General") and "Y" indicates its level ("Yes").

Once all the articles have been coded according to the defined variables and levels, MCA has been conducted and the results are present in Figure 1.2. The interpretation of results is based on proximities between the points (Abdi & Valentin, 2007). Here, the proximity between levels of different nominal variables is studied. When the points are close, it indicates that the two levels (of different variables) are synchronized. In other words, they have seen together in observation and hence between them correlational relationship can be recognized. It is necessary to emphasize that this type of relationship can't indicate any form of causality between the levels of the nominal variables.

Due to the complexity of the problem (4 identified axes), a limited amount of information can be plotted in one graph. The most information represented is 37.4% and it can be seen in Figure 1.2-1. Observing this graph, it can be said that the axes are categorizing the data. F1 divides practical solutions from problem descriptions. This is evident when having in mind that optimization, particular problems, decision-making, frameworks, methodologies and tools are grouped on one side and other variable levels can be seen on the other. F2, on the other hand, separates general solutions from the specific ones. Here, general, non-safety problems, decision-making, tool design and methodology are represented on the same side. Hence, it implies that the general solutions are usually made for decision-making and tool development. Those solutions don't include joint terminology and they are represented in the form of methodology, but also tools. Certain non-general problems are also treated through framework and studies. This is indicated through the other axes represented in Figure 1.2. However, the results from all the graphs need to be interpreted with caution, since the amount of represented information in each graph is less than 50%. Hence, the study should be observed as a general overview that structures the literature review.



Figure 1.2 MCA results: a) Axes F1F2 – 37.4% of information; b) Axes F1F3 – 34% of information; c) Axes F3F2 – 30.81% of information; d) Axes F1F4 – 31.4% of information; e) Axes F4F2 – 28.22% of information.

More information can be obtained by comparing distances between individual levels of nominal variables across the graphs:

- Proximity of Use-Decision-making ("U-D") and Maturity-Methodology ("M-M") indicates that the methodology is often used to represent decision-making problems.
- Presence of F1 axis clearly shows that particular problems are solved in the form of tools.
- General approaches are always non-safety and non-general approaches are safety oriented.
- The general approaches address mainly analysis and monitoring.
- Approaches that have joint notion of risk are usually non-general and safety oriented. This group is on the opposite side from the approaches without joint notion of risk that are general and non-safety oriented.
- Optimization problems usually impose joint terminology.
- Optimizations solutions are closely related also to tools. The three (optimization, joint terminology and tools) can often be seen together.
- Optimization addresses evaluation phase of risk management.
- Studies are usually performed in particular area.
- Tool development is not often performed and, when it is, it is more general than not.
- Approaches that are addressing assessment, all phases of risk management and none of the risk management steps are considered common due to their distance from the center.
- The studies are rarely conducted. Hence, this computer-aided literature study can represent a contribution on its own due to the lack of synthesized information on risk in engineering.

As a conclusion of the conducted study, two main observations regarding the research direction of the thesis can be stated. Firstly, as expected, optimization and particular problems are solved in the form of tools. Since the decision-making is usually addressed through methodologies, clearly there is a need for the general software solution. Secondly, those solutions ask for statistical or data-driven approaches. This is justified by the fact that so far these solutions mainly don't include joint terminology. Hence, risk is usually solely identified with the help of experts and often can be qualitatively of quasi-quantitatively described. Consequently, **the thesis can focus on general approach that is to be formed as a tool that can support statistical analysis.** 

## 2.3. Analysis of general decision-making approaches

While the general study on risk management in engineering has provided a good insight in the field, it has also provoked certain questions. The need for general decision-making approaches has been shown by the practice and by the scientific community. The previous analysis also implied the direction by which the research can be conducted – towards software solutions that can include statistical view on risk. And since this information can represent only a glimpse of the scientific gap, the additional analysis has been conducted. To pursue in the objective manner, this new study has used the same sample of articles. From 220 initially identified, 19 articles focusing on general decision-making have been selected for further analysis. These articles are the only articles of the whole sample that belong to this category.

The new articles have been analyzed with the previously shown practical issues in mind. Hence, the following was tracked:

- The maturity level. Similarly as in the first study, the goal has been to judge the time-to-automation.
- Orientation towards project and product. Since the goal of the thesis is to provide global projectproduct solution, this parameter may indicate the amount of effort needed to merge the two aspects.
- Reference to project management and inclusion of the process. As explained earlier, project or development process and risk management are both processes. Hence, it is essential to observe if the solution takes into account any process and more precisely if the interactions between the processes of interest are identified.
- Multi-result, causality, different actors and their interactions. The practice has shown the need for the solutions that can take into account propagation and interactions. Hence, these parameters have been identified to track this.
- Product aspect and subsystem interactions. In case that the article focuses on the product, it is important to notice what aspect of product have been treated. Hence, "N" indicates no specific product aspects, "S" indicates structure, "F" functions and "B" behavior of the product. Related to the previous it has also been determined if the article takes into account any form of granulation of the product and the interactions between different levels.
- Requirements. Lastly, since the focus of the thesis is design process, it is essential to track if certain solutions take into account its main input requirements.

The obtained results are summarized in Table 1.2.

	Referring to PM	Maturity	Product-oriented	Project-oriented	Process included	Multi-result	Causality	Different stakeholders	Interaction between stakeholders	Product aspect	Requirements	Subsystem interaction
(Gidel et al., 2005)	Yes	Methodology	Х	Х	No	No	Yes	Yes	No	Ν	No	No
(Vrijling et al., 1998)	No	Methodology	Х		No	Yes	Yes	Yes	Yes	Ν	No	No
(Wertz & Miller, 2006)	No	Tool	Х		No	No	Yes	No	No	S	No	No
(Lough et al., 2009)	No	Tool	Х		No	No	Yes	No	No	F-S	No	No
(Unger & Eppinger, 2011)	Yes	Methodology	Х		X - Design	No	No	No	No	Ν	No	No
(Krus et al., 2012)	No	Tool	Х		No	No	Yes	No	No	F-S	No	No
(Van Bossuyt et al., 2013a)	No	Methodology	Х		No	No	Yes	No	No	S	No	No
(Goswami & Tiwari, 2014)	No	Tool	Х		No	No	Yes	Yes	Yes	В	Not explicitly	Yes
(Amine et al., 2017)	Yes	Tool	Х		X - Design	Yes	No	No	No	В	Yes	No
(da Cunha Barbosa & de Souza, 2017)	No	Tool	Х		No	Yes	Yes	Yes	No	S	No	Yes
(Gilb, 2003)	Yes	Methodology		Х	No	No	Yes	No	No			
(Kayis et al., 2006)	Yes	Tool		Х	No	No	Yes	Yes	Yes			
(Malotaux, 2007)	Yes	Methodology		Х	No	Yes	Yes	Yes	Yes			
(Kloss-Grote & Moss, 2008)	Yes	Methodology		Х	X - Design	No	No	No	No			
(Marmier et al., 2014)	Yes	Tool		Х	X - Design	Yes	Yes	Yes	Yes			
(Ou-Yang & Chen, 2017)	Yes	Methodology		Х	No	No	No	No	No			
(Antes et al., 2001)	Yes	Methodology			No	Yes	No	No	No			
(Patil et al., 2012)	No	Tool			No	No	Yes	Yes	Yes			
(Cedergren & Tehler, 2014)	Yes	Framework			No-but risk theory	No	Yes	Yes	Yes			

Table 1.2. Analysis of general decision-making approaches

Although articles can be divided into project-oriented, product-oriented, project-product-oriented and business oriented, the distribution between them is not the same. Only one article takes into account project and product aspects together. Gidel et al. (2005) relate project and product risk management through 4 phases. Similarly, only Amine et al. (2017) in their product-oriented solution treat project management aspects. This is at the same time, the only identified article that takes requirements into account. Hence, it is clear that the gap exists between the project and product risk management. In this sense, focusing on the merged solution can be considered justified. The gap becomes evident when the processes are considered. Since only limited number of papers are taking into account any process, it is clear that risk management is often treated separately from its subject of interest. Detaching product risk from the underlying development or project risk from project flow, can be a big approximation and can have a big impact. Sure, in certain cases the underlying processes are considered in the form of risk registers, but it is debatable how much this representation can cover. Hence, there is a need for comprehensive risk management that follows the flow of the observed processes. Going in the similar direction, it is clear that the product in its complete form (explicitly covered through its functions, behaviors and structures) is not fully present. Similarly to the previous, the reason for the lack of inclusion may be in the fact that it requires the representation of the flow between them. This leads us to the similar problem that is seen in the process representation. Hence, it is inevitable to ask if this representation is suitable to represent product risk management.

On the positive side, it is clear that the community is focusing on the relationships between the risks. Most articles are treating the causality, while interaction is present significantly less. Nevertheless, this implies that there is a need for the relationship representation in risk management. Certain articles are addressing the stakeholders and product subsystems showing a necessity for project and product relations. Similarly, in 7 articles, authors are treating resulting risk in several dimensions. This shows the need for different views on risk and potential trade-offs between them in order to make a decision.

As a conclusion, it can be said that this analysis of general decision-making approaches clearly identifies the scientific gap. The lack of connections between the processes, project and the product is evident. The community is working on different relationships in risk management but there is still a way to go. Finally, the need for the solutions that will support decision-making is clear. This all justifies the motivation for the thesis.

## 2.4. On the connection between the scientific gap and the scientific issue and questions

The conducted studies have confirmed the practical need for the global risk management approach in the context of product development. The scientific gap is illustrated in Figure 1.3. As the studies have shown, the current approaches are mainly project or product oriented (see 1 and 2 in Figure 1.3, respectively). The lack of one of the views can act as a hidden risk and lead to the "surprise" events. In that sense, the question of interactions (see the thirds scientific question) between a project or a development process and product is fully justified. The question of project-product interactions in the sense of risk management, hence, represents the main scientific gap and it is represented in 3 in Figure 1.3. However, literature has shown that individually in project and product risk management, there is a need for the advancements in terms of underlying processes, interactions and propagations of risk. This justifies the first and the second scientific questions. Detailed investigation in the general decision-

making approaches, has proven the need in advancements in this area. The tailor-made information is shown to be missing and hence it implies the necessity for the fourth scientific question. Lastly, when creating the risk solution, it mustn't be forgotten to directly address the risk management process. 49% of identified solutions address risk without the clear management perspective. Those solutions are often defining risk through probability, uncertainty or similar form. Having in mind that they are either focusing on optimization or decision-making related to particular problem, their application is highly limited. This implies that the global solutions are not fully covering the need of the practice. With this is mind and with the results of MCA analysis, the need of general approaches that would support statistical data is shown. Hence, the fifth question is aiming to take this into account. In terms of maturity of the solutions, it is evident that the science community is asking for the tools. It has been shown that the



general decision-making solutions are usually developed in the form of methodologies while particular problems and optimization are solved through tools. Hence, the thesis is to cover this aspect as well.

## 3. Research methodology

The main goal of this thesis is to provide the comprehensive project-product risk management solution. Since the literature research has also shown the lack of interactions in the individual project and product works, these areas have been taken into account as well. Hence, the basis for the thesis work can be summarized in Figure 1.4. Defined issues are presented in 1, 2 and 3 and they summarize the scientific gap. Here, 1 represents the lack of project interactions, 2 addresses the intra-product relations, while 3 represents the connection between the project and the product. The solution, is found on the right side of the image and can be seen as the contra-weight of the described problems. Similarly as in scientific gap, it comprises 3 parts: project (depicted in 4 in Figure 1.4), product (depicted in 5) and general project-product solution (shown in 6 in Figure 1.4). The general solution is a joint result of the two individual project and product works. This way, the first three scientific questions are addresses. The other two scientific questions are considered through the connection between the solution and risk management (see 7 in Figure 1.4). This connection implies that in individual solutions as well as in global one, the reference towards risk management problems needs to be addressed. Hence, all the solutions are considering the need for dynamism, different risk views whenever suitable, reference to the risk management phases and adequate results. Also, all of this is shaped in the form of the tool as it is indicated in the previous subsection. Having in mind that from the beginning of this work, optimization is considered as out of scope, the goal has been to develop risk simulator. With the simulator all the requirements can be considered and addressed.



Figure 1.4. Scientific gap and its desired solution

Observing the project (see 1 in Figure 1.5) and product (see 2 in Figure 1.5) risks separately, can be compared to development of just one part of the final product. While this may be considered sufficient to represent certain characteristic of a product, its full functionality can't be achieved. Contact wires in a light bulb need filament to connect them. Same can be stated for risk management. Without process-product connection (see 3 in Figure 1.5), risk management is just partially addressing the problem. Also, as it has been shown briefly in the conducted literature analysis, the current solutions are just partially covering process and product problems in risk management. Hence, the goal of this thesis is to firstly deepen the individual models by representing interactions within process (see 4 in Figure 1.5) and product (see 5 in figure 1.5). On these individual solutions, the connections are to be made (see 6 in Figure 1.5). It is believed that this connection will provide a brighter perspective on risk management in product development projects.



Figure 1.5 The gap and desired solution illustrated on a product

With all the previous in mind, the research methodology includes five parts:

- Part 1: General overview of risk, scientific gap and the main assumptions of the future solution.
- Part 2: Development of risk management simulator for a project or a development process based on the general assumptions.
- Part 3: Development of risk management simulator for a product based on the general assumptions.
- Part 4: Development of general project-product risk management simulator by merging the two individual solutions. Clear representation of connections between a development process and its product.
- Part 5: Case study on the developed solution.

The first part is covered in Chapter 1. Through the issues from the practice and the study in section 2, the scientific gap is identified. The scientific questions and main assumptions are comprised in subsections 1.1 and 1.2.

The second, third and the fourth part are covered respectively in Chapters 2, 3 and 4. The project solution was considered the first since it is the development process that results in a product. The product has been studied after and, once performed, the connections between the two have been represented through the global solution. Since these parts represent the core of the solution, different steps were needed to provide the adequate results. The steps performed are illustrated in Figure 1.6.



Figure 1.6. Research methodology

As it can be seen, for all parts, the same research methodology has been used. The research starts with the identification of approaches that partially or completely address the corresponding scientific question. The results of this step are represented in the form of the state of the art and they are a valuable input into the framework and methodology definition. The second step is, hence, the definition of framework and methodology. In this step, the major ideas of the thesis are elaborated and shown. This step is followed by the simulator development. Here, the development details are provided. In the fourth

step the use description referencing the major risk management phases is presented. Lastly, each part of the solution (project, product or general) is illustrated with an example.

## 4. Expected contributions and boundaries of the thesis

The thesis is built on the previous works performed in the LCFC laboratory. Hence, it can be seen as the extension and connection between them. However, although the main motivation can be shared between those solutions and the thesis, due to the different goals, the proposition varies. Process-product integration has been studied in the laboratory for a number of years, particularly in terms of quality and improvement of manufacturing processes (Bassetto, 2005). The goal of the thesis is to deepen its risk management connection. For this purpose, different works focused on performance evaluation in general (F. Li, 2017) or through the prism of production systems (L.-A. Shah, 2012) have been used as a starting point.

The expected contributions and limitations of the performed work are briefly summarized in this section. Detailed contributions regarding the particular solutions are covered in the appropriate sections.

## 4.1. Expected contributions of the thesis

Chronologically speaking, the first contribution of the thesis is the conducted general state-of-the-art study. While there are different studies on the risk, they are mainly focused on defining the risk or they are addressing the applied approaches. This study provides a general overview of risk in engineering. Hence, it can be considered valuable resource for the initialization of work on the risk.

Apart from the mentioned, the contributions of the thesis can be divided into three main categories: contributions related to project risk management, those related to product and those imposed by the project-product connections in risk management. However, all three aspect should be characterized with comprehensiveness, flexibility and interaction representation.

The project-related risk management approach is to include various facets for product development process. Actors, process plan, information, equipment and their related events are to be covered in the solution. Also, the solution is to be closely related to the process itself, so the development flow would not be burdened and interrupted. It is, hence, expected to provide an approach that would not rely on global risk knowledge, but to the information available to the actors and the users of the approach. Building the solution in this way, requires advances in terms of interaction representation. In standard approaches, the risk is observed globally and relationships between different risks aren't often considered. In this work, it is believed that this manner of dealing with risks is approximative. To overcome this, comprehensiveness and interaction representation advances are needed. Interactions are particularly important in calculation of global risk metrics (e.g. cost and time). Hence, the solution is to cover risk interactivity to build risk bottom-up. Finally, the goal of the thesis is to provide software that helps decision-making. Considering that different risks, the solution needs to be flexible. The flexibility should include multi-path and multi-view risk analysis.

The product-related risk management solution should contribute to the scientific community by providing a comprehensive solution that can show the evolution of product performance based on different risk sources including those related to the performance quality of the underlying development process. Similarly as in the project solution, this comprehensiveness requires interaction between the

drivers and between the product components. In other words, these interactions are to enable product synthesis while representing impacts of different risk drivers. Hence, as the contribution, interactions need to be represented as well. Lastly, it is expected that the solution will be flexible enough to support scenario analysis including simultaneous events and their results comparison.

Finally, the project-product risk management solution should empower the user to approach risk in a comprehensive manner. While certain risk management resources are trying to address the two aspects, no solution is identified to treat it from the systemic, bottom-up, dynamic and flexible point of view. The systemic approach should be based on the definition of project and product that can be built and rebuilt together with their risk like Lego bricks. Hence, no advantage should be given to any of the two mentioned aspects. They should be treated equally and using their area-specific knowledge. The bottom-up approach should enable risk treatment as they can appear in the development process and on both project and product levels. Dynamism and flexibility should permit to investigate different scenarios and to stochastically implement any event. Similarly as in project and product areas, flexibility should provide different point of view on the risks. This solution should enable the representation of "ourselves" as we are and as we work during the development. In this way, we can consider ourselves ready to attack the risk – the enemy that we can never know for sure.

#### 4.2. The main boundaries of the thesis

Certain limitations exist in terms of risk management, definition of risk and application. They are listed in this subsection.

The developed risk approach doesn't include all the phases of risk management. It considers the phases that are in the focus of the majority of engineering approaches - risk assessment. Hence, it covers identification, analysis and evaluation of risk. Risk optimization and, hence, treatment of risk have been considered out of scope. The solution, however, provides the input into decision making by giving the evaluated values of risk (such as time, cost, quality or performance). In this sense, the result can represent an input into multi-criteria decision making (MDM). However, the decision-making process is not included in the thesis and this work is considered complementary. Different MDM modules can be added and tested to suit the need of the user.

In terms of definition of risk, it should be emphasized that the approach is not consider explicitly the failures. Since, the goal of this work is to enable the connection between the development process and the product, the product risk is considered more globally. Rather than focusing on the failure, the thesis is dealing with the performance risk. Since the solution is taking into account the failure-propagation literature, if need be, the failure model can be added to the developed one.

As far as project definition is concerned, the focus of the thesis is limited to the development process. As a result, organizational issues are considered to be out of scope and scarcely represented in the thesis. However, this aspect is considered to be of interest to the extension work.

Lastly, in terms of application it should be noted that from the user perspective, the initial effort is needed to define the initial development behaviour. The solution is general, and hence, can be accommodated to different development processes after this step, but the user is the expert that needs to provide the adequate knowledge to suit the solution to the observed problem. Hence, this step can be considered as time-consuming and somehow complicated. However, it is considered necessary in this phase of the research. The manner of addressing the risk from the behavioural side and bottom-up is new to the community, hence manual definition is considered important to understand and to gain the

confidence into the developed solutions. The future work will deal with the introduction of data mining and learning techniques that can help in automatization.

#### 5. Thesis organization

The thesis is organized in accordance with the research methodology. Hence, every one of five parts, represents a separate chapter of the thesis. The thesis organization is presented in Figure 1.7.

Chapter 1 represents the first part of the research methodology and it is shown in 1 in Figure 1.7. This chapter is based on the conducted study on risk management in engineering. Hence, the main observations are presented together with the definition of scientific gaps and questions. The chapter also summarizes the main ideas followed in the thesis, the research methodology, the contributions and the limitations of the performed work.



Chapter 2 (see 2 in Figure 1.7) is covering the project-related risk management solution. It comprises all the steps of its development: assumptions, state of the art, framework, methodology, simulator development, usage perspective and illustration through the example. The special attention is given to the scientific gap in project area and the manner the developed solution is addressing it.

Chapter 3 (see 3 in Figure 1.7) is related to the product risk management. While all the main areas of development are covered, from the assumptions to the illustrative example, the focus is given on the influence of the project to the product. Hence, the product solution is considered as the result of the underlying development process. The chapter explains what development aspects are taken into account and how are they addressed. The adequate contributions are emphasized at the end.

In Chapter 4, the global project-product solution is presented (see 4 in Figure 1.7). Similarly to previous, the chapter include all the development steps. The special attention is given to the connection between the project and product. The global contributions are addressed in this chapter.

Throughout the thesis, the same development example has been studied – design of a hair dryer. This simple example had a goal to provide the sense of unity between the different chapters and at the same time, through its simplicity, to illustrate the main points in the proposed solutions. On the other hand,

since each solution represent a comprehensive unity, if one is interested in just one part of the problem, the appropriate chapter can be read. For example, those interested in product solution can read Chapter 3 where all the information from initial assumption, through state of the art and solution proposition to the example, can be found.

Chapter 5 (in 5 in Figure 1.7) presents the discussion and conclusion on the performed work. This chapter includes general conclusion and the one based on the requirements in practices. It also stresses the main limitations and the solutions to overcome them. Finally, the chapter and the thesis is finalized with the perspectives.

The thesis is wrapped up with the general conclusion, appendices and references.

# Chapter 2: From framework to simulator for risk management in a development process

#### Abstract

Product development is a complex process that calls for interactions between various actors, equipment, methods and information. On top of that, different problems or risks may impact the process. In this chapter, the comprehensive solution for risk management in development processes is proposed. The solution considers different interactions that are seen in product development. It is based on the separation between individual, rather epistemic, risk events and the behaviour of the system that is considered aleatory. The individual risk event has impact on system parameters. It is this new parameter value that causes the change in the behaviour and consequently in output risks. The solution is made as a simulator. Bayesian networks are used for interactions of individual risk events. Fuzzy Cognitive Maps define risk task behaviour. Multi-agent methodology is used to illustrate sequential and other interactions between the tasks so the risk can be represented on the process level. Monte Carlo simulation is used to obtain probabilities of different output risks. The simulator, hence, gives comprehensive results including event and effect probabilities and different grades in risk effect including stable and chaos states. The simulator is supported by a methodology focusing on risk assessment. Proposed risk assessment includes manual identification and analysis of risks and automatic risk evaluation that is performed in the proposed software. This solution organization supports different views on risks and "what if" analysis.

In this thesis by project, we consider product development process. Due to this focus, the term "project" is presented as "development process" or "process" wherever these terms are considered more appropriate. Hence, its risk can be roughly divided into two aspects: the one related to the development process itself and the ones focused on product including risk related to the result of the development process. The interactions are made between different actors, equipment, information, methods and problems that may appear in different places. The organizational aspect of the project and their variabilities and vulnerabilities are consequently considered out of scope. The product aspect and global process-product solution are presented in Chapters 3 and 4, respectively.

The goal is to provide a comprehensive development process risk management solution that assesses risk interactions and enables decision-making and dynamic monitoring. In that sense, the chapter is directly addressing second, fourth and fifth scientific questions. Second question is dedicated to risk definition and interaction presentation in the context of development process. Hence, it is the core of the chapter. The fourth and the fifth questions are dealing with usage of the solution in a sense of decision-making, dynamic monitoring and risk assessment. Thus, the form of the solution is shaped to meet these goals.

The chapter provides comprehensive view on the developed process risk management solution from its idea to application. It is organized in the following manner. Firstly, risk terminology and state of the art is studied to position the problem in the scientific context. In Section 2 proposed framework and its model are presented. Section 3 deals with the simulator development based on the ideas form the second section. Section 4 provides utilization perspective with the focus on the developed risk assessment methodology. In Section 5 the whole solution is illustrated using an academic example of a hair dryer development process. The conclusions are made in Section 6.

## 1. Risk management in product development: from definitions to the state of the art

In Chapter 1, different views of risk have been briefly mentioned. How the risk is defined influences greatly the results of its management. Thus, in the first section of this chapter, a risk terminology and its analysis are presented. This is followed by the implications of development process for risk management. The third part of this section deals with risk management state of the art in the development projects and/or processes. Finally, the section is concluded with trade-off analysis of all identified solutions and their potential to address the problem treated in the thesis.

## 1.1. Risk terminology and analysis

Risk can be mentioned in daily conversation and in scientific community. In both cases, it can attract attention to the different aspect of the same situation. Some of the risk definitions are: "a possibility of loss or injury"(« Definition of RISK », 2020)(« Definition of RISK », 2020), "the possibility of something bad happening", "a situation that could be dangerous or have bad result", "someone or something that creates or suggest a hazard". This implies that different definitions focus on possibility, situations or events and cause. Other important element of risk is its perception. Renn (2008) draws a parallel between risk and its perception using mythological relation: Damocles' sword (artificial risk source), Athena's scale (confined to monetary gains and losses), Pandora's box (delayed effects) and Hercules' image (personal control over degree of risk). Similarly to possibilities, Larson & Kusiak (1996) observe risk through the scenarios, likelihood and consequence. It is clear, hence, that risk is far more than one term. In ISO 31000, risk represents an effect of uncertainty on objectives. Hence, it can

be divided into and analysed with two notions: effect and uncertainty. With these two terms, all previously mentioned can be covered. It is this terminology that is used further in the thesis.

#### 1.1.1.Risk taxonomy

According to ISO 31010, risk (effect) can be described as a chain of terms including risk source, event, consequence and likelihood. Figure 2.1 illustrates this chain. In the origin of the risk is the source or cause of uncertainty. This source can be everything from events, through decisions to any situations leading to uncertainty. This uncertainty provokes events or series of events. Also, different sources can create a network of events. Thus, this first part of the chain deals with the cause of risk and it is shown in 1 in Figure 2.1. Secondly, as represented in 2 in Figure 2.1, every event leads to a certain consequence or effect. These two elements are described based on our knowledge through likelihood, probability or uncertainty in general. They illustrate the knowledge related the events and the effects. Finally, all the effects are not important if there is no objective or a stake which are influenced by a consequence. This is shown in 3 in Figure 2.1.



Figure 2.1 Risk definition: a) general risk conceptual graph; b) example

All the mentioned can be supported through an example (see B in Figure 2.1). In the context of development process, it is clear that the one of the stakes is the project itself. So, focusing on its objectives it is possible to say: "New technology problems can lead to the increased project cost and time-to-finish." In case the particular new technology is not included in our development process, there would be no risk although the problems would still exist. Also, in the standard definition, risk is often

about the things that we don't know. It is a lot about a source of risk (1 in Figure 2.1) and about its effect (3 in Figure 2.1). The propagation of the problem through the project or system is usually not covered. As seen from the example, it is just emphasized that the problem increases cost and time. How and why it is often left unexplained. And how and why are hidden in the behaviour of our development process. Hence, this thesis focuses on separating unknown (1 in Figure 2.1) and our behaviour (2 in Figure 2.1) to give effect on objectives (3 in Figure 2.1). In order to achieve this, special attention needs to be given to our understanding of uncertainty.

#### 1.1.2. Uncertainty taxonomy

Uncertainty is an attribute for an event and an effect in risk management literature. It represents the deficiency of information, understanding or knowledge related to each term (*31000: Risk Management* — *Principles and Guidelines*, 2009). However, different areas consider uncertainty in different way. It covers many concepts from the intrinsic variability of a phenomena that cannot be reduced to the one that belongs to the lack of knowledge that can be deepen (*Risk Management – Risk Assessment Techniques Management Du Risque – Techniques d'appréciation Du Risque*, 2019). However, the discussion on uncertainty requires the clear distinction between its associated terms (e.g. probability, variability) that depend on the research area. In this section the line between uncertainty taxonomy from different areas has been made so the clear mapping between the terms used in the thesis and the ones from other disciplines can be made.

Extending the work of Morse et al. (2018) and Thunnissen (2003), Table 2.1 summarizes taxonomies that can be found in the areas that are considered related to the thesis subject: design and development of complex systems (Thunnissen, 2003), modelling and simulation in engineering design (tolerance analysis) (Walter et al., 2014), product development (Engelhardt et al., 2011), risk management (Finkel, 1990; Ward & Chapman, 2003), policy and risk analysis (Morgan et al., 1990), system engineering (Klir & Folger, 1988), management science (Bedford & Cooke, 2001), computational modelling and simulation (Oberkampf et al., 1999) and mechanical engineering (Otto & Antonsson, 1993). Table 2.1 maps all the taxonomies on the one developed by Thunnissen that is considered broadest and suitable to cover the aspects that are addressed in the thesis. As it can be seen, notion of uncertainty diverges highly from area to area. What is considered in one domain, is not covered in the other. However, the connections can be and are made, as shown in the table.

These different types of uncertainty address different aspect of the thesis. Firstly, starting from the basic separation between aleatory and epistemic, the distinction can be made between the individual risk events and the behaviour of a development process. Risk events are generally considered epistemic and partially known. Since they are in direct focus in any risk description (as seen in Section 1.1), they are represented with numerous existing techniques (e.g. FMEA). However, in this area there is always room for a surprise. Hence, they justify their status of the enemy that can never be fully known. The behaviour of the development system, however, should be in the greater sense represented as an aleatory uncertainty. Hence, it can be described with parameters and their distributions. Thus, it is assumed that it is possible to get to know ourselves. Only with this in mind, we can fight the enemy. On the other hand, it should be emphasized that, this division still holds certain phenomenological, modelling and behavioural epistemic uncertainty that are consider as negligible.

Uncertainty										
(Thunnissen, 2003)		(Walter et al., 2014) (Engelhardt et al.		et al., 2011)	(Finkel, 1990)	(Ward & Chap	apman, 2003)			
Ambiguity					Decision-rule uncertainty	Uncertainty about objectives and priorities				
Epistemic		Uncertainty in data	Unknown			Uncertainty about design and logistics				
	Model	Uncertainty in model and simulation – mathematical model			Difficulties in modelling process					
Phenomenological		Phenomenological uncertainty Uncertainty in model and simulation - concept			Parameter uncertainties	Uncertainty about objectives and priorities	Variability associated with			
	Behavioural	Uncertainty in human behaviour Uncertainty in model and simulation – programming		Estimated			Variability associated with estimates Uncertainty about the basis			
Aleatory		Uncertainty in data Uncertainty in model and simulation – visualization of effect	Stochastics		Parameter uncertainties Temporal, spatial, or interindividual variability	Uncertainty about design and logistics Uncertainty about objectives and priorities Uncertainty about fundamental relationships between project parties	of estimates			
Interaction						Uncertainty about fundamental relationships between project parties				
				Uncerta	inty					
(Thunnissen, 2003)		(Morgan et al., 1990)	(Klir & Folger, 1988)		(Bedford & Cooke, 2001)	(Oberkampf et al., 1999)	(Otto & Antonsson, 1993)			
Ambiguity		Linguistic imprecision Decision variable	Ambiguity				Imprecision			
Epistemic		Randomness	Vagueness		Epistemic	Uncertainty Error	Possibility			
	Model	Approximation Model domain parameter			Model					
Phenomenological Behavioural		Approximation; Decision variable; Value parameter; Outcome criteria			Parameter		Imprecision			
		Approximation; Subjective judgement; Disagreements			Volitional					
Aleatory		Statistical variation: Subjective judgement: Variability			Aleatory	Variability Error	Probabilistic uncertainty			
Interaction										

Table 2.1 Uncertainty taxonomy based on (Morse et al., 2018; Thunnissen, 2003) and extended

Other types of Thunnissen's uncertainties are also represented in the thesis. Ambiguity is included by considering requirement vagueness. Finally, the central part of the thesis is based on interaction uncertainty. Uncertainty that is, based on the information summarized in Table 2.1, often neglected or not treated explicitly. Thunnissen's work underlines the importance of this uncertainty. He points out that one possible way to address interaction is through simulation, which is all in accordance with the main ideas of the thesis.

#### 1.1.3.Risk evaluation

The first question that comes to mind after defining risk is how to quantify it. One of the most common way to calculate risk directly originates from its ISO definition:

$$RPN = S \cdot O \cdot D$$

where RPN represents Risk Priority Number, S is severity, O represents occurrence and D is detectability. This manner of calculating risk and consequently prioritizing risk is used in standardized methods (like FMECA) or specific ones. In certain cases, however, it doesn't include detectability. In others, it slightly changes its form (Smith & Merritt, 2002):

$$L_e = P_e \cdot P_i \cdot L_t$$

where  $L_e$  represents expected loss,  $P_e$  probability of risk event,  $P_i$  probability of impact and  $L_t$  total loss.

Although these quantitative measures can be calculated from actual values, this is often not the case and the risk priority numbers are determined based on an expertise and experience. Also, this type of quantification is more suitable for defining criticality and prioritizing risks. Hence, they can say how risky something is comparing to the others, but they provide no information on interactions and their consequences. For this purpose, other approaches must be used – the methods oriented toward analysis of consequence, dependencies and interactions.

The techniques for representation of consequence and likelihood, and for dependencies and interactions are summarized in the Table 2.2. The classification is based on ISO 31010 and selected according to their ability for quantitative risk representation or the link between quantitative and qualitative.

Similarly to conclusion of the survey in the first chapter, it can be said that one single method can't cover all the aspects that the thesis addresses: qualitative measures for likelihood and consequence and inclusion of interactions. Although different solutions are addressing consequences numerically, the main issue is that they are scenario-based with the focus on determination of probability of effect. Hence, different effects are in those cases predetermined and they are not related to the system behaviour explicitly.

IEC TR 63039 (*Probabilistic Risk Analysis of Technological Systems*, 2016) proposes usage of FTA, ETA and Markov chains to determine rate of the final event knowing the initial state. This standard makes a step forward the separation between the system's behaviour and risk events. However, it is more suitable for product risk analysis than the one related to the development process due to the identification of relevant states concerning numerous stakeholders and their interactions.

ISO 31010 lists only two approaches that are capable to deal with the interactions and dependencies. One of those two approaches provides only qualitative information while the other is considering only probability. Hence, they are considered inadequate. However, in the group of causal maps there are solutions that can be used in quantitative sense. They are currently not covered by ISO 31010, but are

present in scientific community. The example of this type of maps is Fuzzy Cognitive Map. This again calls for the further analysis of the approaches.

Approach	ISO category	<b>Description / Mathematical formulation</b>						
Bayesian	Consequence	Bayesian analysis is used to analyse likelihood on events based on prior judgements						
analysis and	and likelihood	and empirical data. Bayesian network is used for risk estimation. It includes						
Bayesian		(conditional) variables and their cause and effect relationships.						
network		Bayes' theorem:						
		$P(A B) = \frac{P(B A)P(A)}{P(B)}$						
		P(A B) – probability of A given that B has occurred (the posterior assessment)						
		P(B A) – probability of B given A has occurred						
		P(A) – the prior assessment of the probability of A						
		P(B) – the prior assessment of the probability of B						
		Bayes theorem can be extended to consider multiple events.						
		Bayesian networks are based on Bayes inference and they posses the same properties as Bayesian analysis						
Business impact	Consequence	Business impact analysis consider influence of incidents and events on organization						
analysis	and likelihood	and the means to manage them.						
		It is performed using questionnaires, interviews and/or workshops.						
Event tree	Consequence	Event tree is the analysis of consequence and controls that give both quantitative and						
analysis	and likelihood	qualitative results. It is used to model and analyse the probability of outcomes scenarios based on the given event and controls. Qualitative results include descriptions of potential outcomes.						
Fault tree	Consequence	Fault tree is used for analysis of likelihood and causes. It analyses causes of events						
analysis	and likelihood	based on the faults and Boolean logic. It provides both qualitative and quantitative results. Qualitative result includes graphical representation and a list of minimal cut sets.						
Cause –	Consequence	Cause-consequence analysis approach provides quantitative results for cause and						
consequence analysis	and likelihood	consequences. It is a combination of Event and Fault trees.						
Markov analysis	Consequence	Markov analysis is used to analyse likelihood. Calculates the probability that the						
5	and likelihood	system will be in one of its states at defined time in the future.						
Monte Carlo	Consequence	Monte Carlo simulation is used to calculate probability of outcomes through multiple						
simulation	and likelihood	iterations and random variables.						
Causal mapping	Dependencies	Causal mapping is used to analyse cause qualitatively. It represents events, causes,						
	and	effect and their relationships.						
	interactions							
Cross impact	Dependencies	Cross impact analysis provides quantitative results on likelihood and cause. It						
analysis	and	considers the change in the probability of an events based on the occurrence of one of						
	interactions	them.						

Table 2.2 Techniques for risk consequence, dependencies and interactions analysis based on ISO 31010

Extended analysis of joint approaches, non-standardized approaches or the application of standardized approaches in the product development context is provided in Section 1.3 of this chapter through the targeted state-of-the-art analysis.

#### 1.2. Development process implications towards risk management

After analysing the preferable risk terminology and approaches for its quantitative representation, the relation between risk and development process should be observed. This relationship can justify some assumptions made at the beginning of this work: uncertainty and complexity. To begin with, in the thesis, development process is considered through the prism of project management. Hence, it is represented as temporary endeavour undertaken to create a unique product, service or a result (Project

Management Institute, 2013). In other words, it is a temporary organization to which resources are assigned in order to deliver a change (Turner, 2007). The resources mentioned can include everything from actors, stakeholders to equipment. Each of them can be a source of risk, the effect of events or the contributing factor to the overall consequence on objectives. Consequently, risk and project management go hand in hand. Project Management Institute (2013) treats risk management as integral part of project management. Although in practice the joint evolution of processes and risk management is not guaranteed, the goal is to provide one. In that sense, characteristics of risk management need to be aligned to the needs of the project.

Observing the development thorough the generic design process, 6 main phases can be identified: planning, concept development, system level design, detail design, testing and refinement and production ramp-up (Eppinger & Ulrich, 2015). From the product perspective, each of these phases can be characterized by certain type of uncertainty (Morse et al., 2018): conceptual design copes with epistemic uncertainties, system level design aims at integrating aleatory uncertainty, detailed design treats interaction uncertainty, while testing and refinement focuses on aleatory and interaction uncertainties. From the project perspective, dealing with the product uncertainties through numerous resources with their communication, collaboration and integration leads to the presence of all uncertainty types. In simple words, the risk management problem for product development can be considered complex. But, it is inevitable to ask, how complex this problem is in scientific terms?

Each project lies on the spectrum between simple, complicated, complex and chaotic (Bakhshi et al., 2016; Gorod et al., 2008). Distinct from the simple one, complex project can be chaotic, networkcentric, heterogenous, indeterminable, large and characterized by independence and decentralization (Bakhshi et al., 2016). Different levels of these factors position the project on the complexity bar. Having this in mind, risks in the project environment that naturally embraces several (if not all of this factors) surely belong to the complex problems. In that sense, observing the risk without taking into account complexity of a project would be considered as an inadmissible approximation and a legacy approach. The question is, how to attack risk in these systems? In recent years, risk management is turning towards systemic views and connectivity of risks (Helbing, 2013). To address the problem of complexity, this thesis is oriented towards ubiquitous and cascade risk interactions being one element of the dynamic complexity (Helbing, 2010). Regarding the approaches suitable to solve this task, Helbing (2010) list several ones including: large-scale data mining, network analysis, system dynamic, scenario modelling and agent-based modelling. In that sense, in order to determine appropriate manner to address the problem, subsection 1.3 studies and compares these and other solutions.

## 1.3. Risk management state of the art in the context of development projects

To treat interactions in the complex systems means to be able to represent the perturbance propagation from one end of the system to the other (Helbing, 2013). Instead talking about the butterfly and the wind on the other side of the planet, in the context of development projects, these "ends" connect human resources, means, external stakeholders, tasks, event and effect on the objectives like cost and time. While in previous sections (see Chapter 2, sections 1.1.3 and 1.2) certain methods have shown the potential, further analysis has been conducted to determine the current state of the art on this subject.

To take into account different goals set by the scientific gap, the articles have been studied from the perspective of development process and risk behaviour representation and risk propagation. Since the main goal of the observed solution is risk management, the development process category shows if the solution is capable to consider process evolution. Risk behaviour shows the core of risk calculation. In this category it is tracked if risk of more than one objective has been developed (i.e. cost, time, quality, environmental and others). The risk propagation emphasizes if the observed solution is considering risk

flow through process/system or if it displays impacts between project and the product. The most relevant articles based on the defined aspects are shown in Table 2.3. The full analysis can be found in Appendix 1.

Paper	Maturity	Focus	Development process	Risk behaviour approaches (* indicates the multi-dimensional results)	Risk propagation
(Tyson R Browning & Eppinger, 2002)	Tool	Project	Yes	Simulation + DSM	Yes
(Kayis et al., 2006)	Tool	Project	Not included	Multi-agent + Bayesian Network	Yes
(Lazzerini & Mkrtchyan, 2011)	Tool	Project	Not included	Fuzzy Cognitive Maps	Yes
(Bosch-Mauchand et al., 2012)	Tool	Project	Yes	Value chains simulator	Yes
(Rodney et al., 2015a)	Tool	Project	Not included	Model-based approach	Yes
(L. A. Shah et al., 2016) Too		Process and Product	Yes	Value-risk based decision making + simulation	Yes
(Jamshidi et al., 2018a)	Tool	Project and Product	Not included	Fuzzy Cognitive Maps	Yes
(Jahangoshai Rezaee et al., 2018) Tool		Project and Product	Yes and no	PFMEA and Fuzzy Cognitive Maps	Yes
(Zheng et al., 2018)	Tool	Project	Yes	Bayesian network	Yes
(Gorecki et al., 2019)	Tool	Project	Yes	Papyrus, UML, simulation	Yes
(Shojaei & Haeri, 2019)	Tool	Project / Supply Chain	Not included	Grounded theory, Grey relational analysis, Fuzzy Cognitive Maps*	Yes

Table 2.3 Selected project-related risk management solutions

Firstly, it can be noticed that processes are seldom treated in risk management. The solutions where the process is not considered, are representing risks independently or in the global manner. In that case, the risk is not modelled on the levels lower than the project itself, hence the propagation within it can't be observed. These solutions include Bayesian networks, Fuzzy Cognitive Maps or graph-based propagation (Jamshidi et al., 2018a; Kayis et al., 2006; Lazzerini & Mkrtchyan, 2011; Shojaei & Haeri, 2019). However, these models can be used to address the process. Zheng et al. (2018) combined activity approach with Bayesian network, so engineering tasks are representing nodes of a Bayesian network. This way, the process is included but not exactly in a way of real-life step-by-step development. Another manner to partially include process evolution is by combining Bayesian network with Process Failure Mode and Effect Analysis (PFMEA). This can provide process overview through PFMEA but it has limits of this approach. Hence, the connections are not presented explicitly.

To address the lack of explicit risk propagation through the process, the value-chain models can be used (Bosch-Mauchand et al., 2012; Tyson R Browning & Eppinger, 2002; L. A. Shah et al., 2016). In this approach, every process task with its value influences the overall risk value. Hence, it is a bottomup approach where, as the risk progresses, we move from individual to the higher, system level. Similar idea can also be seen in UML or SysML MBSE models (Gorecki et al., 2019). Another approach that addresses process task is based on DSM or MDM (Tyson R Browning & Eppinger, 2002). This approach is capable of representing the influence of a change or a faulty information between activities. Second problem rises with the risk behaviour representation. Methods that provide propagation through the process usually don't provide additional calculation on risk on the activity level. The goal in these approaches is to calculate the propagation and the individual activity risk represents simply an input. This means that these approaches can't be used for the calculation of risk on the task level. On the other hand, network-based approaches can. Bayesian networks are useful for representing probabilities of different effects. However, the continuous consequence space is not easily tracked with this method. Contrary, Fuzzy Cognitive Maps are easily dealing with this problem.

In terms of behaviour, one more group of approaches can be identified – the one dealing with dynamism and different stakeholders involved in the project. These solutions are based on multi-agent systems to adapt to the specific needs of the model (Kayis et al., 2006; Rodney et al., 2015a). These models are characterized with flexibility, different point of view and integration of individual stakeholders, but in terms of risk they require additional approaches to define the calculation.

Having all previously mentioned in mind, the solution that can fully address the scientific issue haven't been identified. However, different solutions show potential to address specific aspect of the observed problem. They are summarized and compared in the following subsection.

## 1.4. Comparison and conclusion on the approaches identified in the literature

This chapter aims at comparing identified solution from the perspective of the scientific question of the thesis. Identified issues are presented in Figure 2.2. They represent the requirements that the solution needs to meet.



Figure 2.2 Requirements for development process risk management solution

The solution developed and presented in this chapter is focusing on second scientific question related to development process risk. It that sense, it needs to provide adequate process modelling and process risk behaviour. As it can be seen in Figure 2.2, project / development process representation and modelling represent the core of the behavioural model shown through risk interactions and propagation. Apart from this core question, the solution needs to be adequate in terms of risk management (Question 5 in Chapter 1) and decision-making support (Question 4 in Chapter 1). These issues are, hence,

represented in the base of the requirements. "Risk management" indicates that the solution needs to support identification, analysis and assessment of risks. "Dynamics" refers to dynamic risk assessment required in Question 4.1 (in Chapter 1). "Tailoring" corresponds to tailoring of risk information to different decision-makers (Question 4.2 in Chapter 1).

For this reason, the analysis of identified approaches is divided into four axes: risk behaviour, process integration, simulation solutions and general approaches.

**Risk behaviour** is the central category in terms of risk modelling. It aims at identifying the solution that can adequately consider the evolution of the effect on objectives and the potential chaos that the risk can cause. The importance of this problem is directly related to the complex systems and described in subsection 1.2 and the corresponding literature. Since the goal of the solution is to develop a tool (simulator to be precise) the results should be quantitative. On the other hand, having in mind that the current risk management approaches rely often on expert opinions, it would be an advantage if the solution can handle qualitative aspects as well. Likelihood of each event or effect should be taken into account. Lastly, the coverage of interactions and causalities is a must.

The comparison of different approaches is shown in Table 2.4. Fuzzy Cognitive Map (FCM) is a type of causal map where nodes can represent different factors and where links define relationships between them. This type of approach represents the best candidate for the risk calculation since it takes into account interactions and causalities and extends the causal maps presented in ISO 31010 by considering quantitative results. Also, this approach is the only identified approach that can show the evolution of risk effect and that can even enter the state of chaos depending on the states of individual nodes. However, naturally it can't represent the likelihood. For that reason, it should be combined with other solution. Due to the connection that exists between FCM and Bayesian network (through the existence of Bayes cognitive maps) this solution shows the greatest potential. Qualitative system dynamic is another solution that can be used in similar problems. However, its representation of variables using stock and flows is not easily mapped to the socio-technical systems like development processes.

**Process integration** deals with the problem of process representation in risk management. This problem includes possibility for bottom-up process integration due to the representation of the process in the sense of system engineering (as presented in assumptions). Iterations are natural part of every development process; hence they should be included in process representation. Lastly, in the assumptions it is assumed that the solution should be global enough to be able to accommodate to different processes.

The two approaches that can address the process, value chain and DSM and MDM – inspired approaches are almost equally adequate to represent the process integration. However, since the value-based approach is closely connected to system engineering and can be used as a pattern in the engineering processes (Wu et al., 2017), this solution is considered more appropriate.
Criteria →		R	lisk be	havio	ur		Pro	ocess integra	tion		Si	mulation		Gen	eral
Method ↓	Effect calculation - grades	Effect calculation - chaos	Likelihood	Quantitative	Qualitative and quantitative	Causality and interactions	Patterns	Bottom-up process integration	Iterations	Multi-view	Stakeholders	Emergent behaviour	Dynamic and Flexibility	Not data demanding	Ease of transition
Bayesian network			Х	Х		Х	Х				Х				
Markov chain			Х	Х		Х	Χ						Х		
Cause and consequence			Х	X		Х								Х	Х
Causal mapping						Х	Х						Х	Х	
Cross impact analysis			Х	X		Х	Х							Х	
Fuzzy Cognitive Maps	Х	Х		X	X	Х	Х			Х			Х	Х	Х
Value chain + MBSE						Х	X	Х	X			Х	Х		Х
DSM, MDM						Х		Х	Х			Х			Х
Discrete event simulation						Х	Х		Х						Х
System dynamic	Х			Χ		Х	Χ		Х		Х				
Agent-based simulation						Х	Х	Х	Х	X	X	Х	Х		
Monte Carlo simulation			Х	Х										Х	Х
Large-scale datamining				Х		Х									

Table 2.4 Analysis of identified approaches comparing to the scientific question

**Simulation** has been identified in Chapter 1 as the most appropriate solution to support decisionmaking. In that sense, the goal of the analysis presented here is to identify adequate simulation type. As it can be seen in Table 2.4, the most adequate simulation method is agent-based simulation. In accordance to Helbing's (2010) observations, this approach has a big potential to individually fight against systemics risks. In the context of the thesis it shows the biggest flexibility and possibility to take dynamic of the events and processes into account. Also due to different classes it naturally can include multi-view and stakeholder behaviour and interactions if need be. In general, agent-based solutions are considered especially adequate for large scale problems, modular domains and frequent changes (Barbati et al., 2012). Hence, they can treat numerous risks and different events and/or process dynamics. Agent-based systems are suitable also for optimization of these problems (large scale, modularity and changes). Hence, they can also be used if the optimization is needed.

**General** requirements presented in Table 2.4 deal with the data demand and ease of transition from the current point of commonly used risk management solutions. Although generally speaking, large-scale data mining represents the unbiased solution for interaction and causality determination, it is considered hard to implement at this time. In the environment where risk is often treated using solely identification methods (like FMECA) or where likelihood approaches are not often considered, it is considered too optimistic to assume that sufficient data can be collected to apply this method. However, other methods that are closer to the current solutions can be used to take into account interactions and to be in accordance with the identified problems of complex systems. This is the idea followed in the thesis. In that sense, Monte Carlo simulation is the preferred approach to obtain global likelihood by taking into account interactions in the previously described model.

The integration of all the mentioned methods into a joint approach is unique and not identified in the literature. It owns its uniqueness to the comprehensive scientific question since other identified solutions are usually treating just parts of the presented problem. The approach from its framework, through the simulator to the application based on the academic example is hence presented in the remainder of this chapter.

# 2. Risk management in a development process – the proposed framework and the model

It is hard to imagine that an ill bat could cause global health crisis and economic problems. Yet, this is the possible cause of events in 2020. While it is certain that all the events can't be predicted, the system can however be prepared to the disturbances. Again, getting to know the events that may cause the problem means to get to know the enemy. However, it is more important to know our own behaviour.

As seen from the literature analysis, risk analysis tools are usually about the likelihood of events, while determining nuances of different states is not often the case. Risk management for development process needs to cover both. Determining what can cause different parameters of a system to change is more about likelihood analysis. How the system reacts on a changed parameter, is more in the second group. While it is not time and place to discuss how come we are more interested in "fortune-telling" or epistemic uncertainty than in determining how can we represent our own behaviour through aleatory and interaction, this thesis aims at focusing on the second one (aleatory and interaction) and providing a connection with the first one (epistemic). Again, as stated at the beginning of the thesis, everything starts with getting to know ourselves. From the ancient times, the enemy or the unknown comes the second.

Section 2 of this chapter starts with the main idea behind the solution for risk management in development process (subsection 2.1). The solution is then developed into the framework (subsection 2.2) and corresponding model (subsection 2.3).

#### 2.1. Risk management in a development process - the main idea

In this work, causes or risks are considered separately from a development process. Development process is observed as a (complex) system whose output represents a risk effect on objective. This main idea is illustrated in Figure 2.3.



Figure 2.3 General idea behind the proposed solution

As it can be seen, risk events (see 1 in Figure 2.3) affect a system behaviour (see 2 in Figure 2.3). This event can be any external circumstance that can lead to the change in a system. In terms of current situation in the world, it can be a lockdown in China leading to the availability issue of a vendor involved in the observed development process. The influence of this and any other risk event is seen as system behaviour. In order to understand this behaviour, the mentioned can be divided into parameters or risk factors (see 3 in Figure 2.3). One parameter can influence another (see 4 in Figure 2.3) and together they form a graph or a network of interconnected relations. The output of this network is the output risk or the targeted effect on objectives (see 5 in Figure 2.3). This manner of decomposing process risks can give more detailed information on objectives since they are considered to be part of a system behaviour. In this work, output risk is a system parameter of a particular interest. Hence, it evolves as the whole behaviour evolves. In that sense, even the parameter that is not considered as an output risk in one view can be observed as the objective in another without the change of the model structure.

Observing it from the example of unavailable Chinese vendor, we can say that these new circumstances cause the change in vendor reliability parameter of the observed development process. Hence, while the quality of a service from the vendor can still be the same, the new schedule and work from home may lead to the late information arrival. It is this new parameter value that propagates through the network of relations, changing other parameter and leading to the final cost and time consequences. Standard risk statement "Health issue in China led to vendor unavailability and cost and schedule slipping", doesn't provide enough information nor confidence. The events are covered in detail but the development system itself is seen just through the cost and time consequences.

Imagine the following question: "What will happen to the development process if I have severe reliability issue of this particular vendor?" FMECA, a tool often seen in project management literature, based on the cause and effect can't provide an answer to the question. Tools related to likelihood

analysis can provide an answer, but the focus would here be on probability of different effects not on the effect itself. Hence, they would also require information about events and their probabilities. The proposed model assesses the risk differently and, thus, can reply to the question. Here, the value of the reliability parameter can propagate and lead to cost and time effect. What can cause that reliability issue can and should be studied separately. In this model, this information is obtained based on the database of risk events described similarly as in the case of the mentioned Chinese vendor. The effect, on the other hand, doesn't depend only on that event but on the state of the system in general. Relationships within the system are those who push the event to have an effect on objectives.

To conclude, it can be said that risk events or causes are observed individually while risk behaviour of a system is considered as general and its relations can be represented independently from the events causing disturbance. The following subsection elaborates this idea in detail and forms a framework.

# 2.2. Risk management in a development process – framework proposition

As stated before, the goal of this work is to enable bottom-up integration and interaction of risk with the clear distinction between risk events and risk behaviour. To move from a general idea to the framework, several concepts have been included and connected. They are represented in Figure 2.4.



Figure 2.4 Conceptual framework of the proposed solution

The effects of a risk event are firstly visible on the level where the development is performed. The designer absenteeism is firstly visible on a design task and it is later that its influence on the cost or time of the whole development process can be seen. The people touched by the risk are the ones with their hands on the development. But when those are asked to report the risk, they should talk in general numbers. They should talk about the global process outcomes. And this is sometimes (or usually) not their area of expertise and, hence, the process becomes time consuming and bureaucratic. For this reason, in this work it has been decided to swap the general development process risk models with the one that builds the risk consequences block by block. The development process has been divided into

tasks (see 1 in Figure 2.4). It is assumed that those tasks, just like the parts of the complex system, can be standardized for the most development processes. In other words, they can be decomposed into set of defined procedures that can be performed by different actors in different processes with different goals. The example can be a market analysis for two different product types. Although actors and results of the analysis will surely be different, the task itself can be made out of same general set of procedures. In the same way, based on its type, the task can have its (general) risk (see 2 in Figure 2.4).

With previously stated in mind, it can be said that task risk is decomposed into set of risk factors (see 3 in Figure 2.4) that are considered important for the task type. Each risk factor has its current value that depends on one or more risk events (see 4 in Figure 2.4). Risk factor is hence an entry point from which risk events propagate into a development process. Those events are all represented with their probability (see 5 in Figure 2.4) and severity (see 6 in Figure 2.4). Thus, the events are the causes of the change and they are separated from risk factors. Their influence is seen through the risk factor value, but the change of the value is a consequence of an epistemic event. In other word, the current value of a risk factor is a consequence of the available knowledge on the risk events impacting the risk factors. For this reason, there will always be a part that is unknown and that can perturb a risk factor value.

Risk factor value on the other hand has known upper and lower boundaries. Each risk factor is connected with at least one other. This network of risk factors forms risk task behaviour (see 7 in Figure 2.4). As a result of perturbance in value of one or several factors, risk progresses through the network of factors resulting in the change of the objective of the development process. The objective can be cost, time, quality or any other parameter of interest for the stakeholder and the development process. This factor is called "task output risk" (see 8 in Figure 2.4).

The development process (see 9 in Figure 2.4) is composed of tasks. The information obtained in one task can be used as input into another one. Similarly, the output risk of previous task influences the next one. Through the precedence relationships between tasks, the task output risk passes from one task to the other until it forms the final risk. This connection is direct and multiple. One activity can directly impact one or more following activities. It should be emphasized that the solution also considers indirect impact between activities through their risk factors. This is detailed further in this section. Development process output risk (see 10 in Figure 2.4) is hence the result of the last task performed in the process that has considered all the previous tasks.

These main concepts are supported with the adequate modelling methods, Figure 2.5.

Distinction of the development process into its tasks isn't a new approach. Shown in 1 in Figure 2.5, the definition of standardized development task is taken from systems science and can be formulated as follows: the activity or tasks represents a set of time and resource consuming actions whose performance is either necessary or contribute to the outcome realization (Walden et al., 2015). In that sense this work is linked to all major literature resources from this area including the corresponding standard (*ISO/IEC/IEEE 15288 Systems and software engineering — System life cycle processes Ingénierie des systèmes et du logiciel — Processus du cycle de vie du système*, 2015). It should be noted, however, that the task and activity are used as synonyms and decomposed into actions. This might deviate from ISO/IEC/IEEE initial terminology, but it is done to align activities and engineering task in a design domain. The general idea of the proposed risk management solution is shared with Model-Based System Engineering (MBSE) through its commercial-of-the-shelf (COTS) and pattern definitions (Wu et al., 2017), 2 in Figure 2.5. The commercial-of-the-shelf approach justifies the standardization in systems. Here, the system can be represented in different granulation by using pre-defined component. In our case, these components are engineering tasks. How engineering process can be decomposed using the task to form a generic system model is justified by the use of patterns. The two mentioned, are the main

tools for the representation of engineering knowledge in MBSE. Hence, it is justified that the generic model proposed here can be developed and later adapted to meet the actual needs in the specific development processes.



Figure 2.5 Main concepts and their approaches

Modelling of risk event is performed using the approaches from the literature. As emphasized in the literature analysis, Bayesian network (see 3 in Figure 2.5) shows the biggest potential to be used in the thesis context. Firstly, like other similar methods, it is used to calculate likelihood based on conditional probabilities. Secondly, it is related to the method used for risk task behaviour and, if need be, the trade-offs between the two can be made. It needs to be noted, however, that the modelling of risk events requires certain amount of data. The final probability depends on the individual and conditional probabilities of all involved events. This information is not always available. When we consider that in PMBOK one of the methods recommended for risk management is FMECA, it is clear that based solely on this information, the model can't be made. For this reason, risk factor values and their probabilities can also be defined by the experts (see 4 in Figure 2.5).

Fuzzy Cognitive Maps (see 5 in Figure 2.5) are used to model risk behaviour. As explained before, risk behaviour consists of risk factors and their relationships. Fuzzy Cognitive Map (FCM) is a causal map that is capable to calculate the emergent influence between factors. Being in the heart of risk calculation, more information about FCM is presented in subsection 2.3.

Due to their capabilities to capture individual behaviours and to represent emergent results and dynamics, the risk management solution is realized using agent-based methodology. Agent-based simulation is used for handling task precedence and process dynamics. Using this modelling approach leaves the space even for the extension. For example, behavioural models for different actors can be merged with the risk model.

All the concepts and their appropriate development methods have now been selected. The next subsection goes further into their integration and functioning through the description of the proposed model.

#### 2.3. Risk management in a development process – the model

When the solution requires coordination of several methods to attain its objective, the question that must be imposed is how these different approaches are combined into a consistent unity. In this section the comprehensive model is presented and mapped to the main axes of the thesis.

The illustration of the model is shown in Figure 2.6. As it can be seen in 1 in Figure 2.6, the activity agent is the carrier of the risk information and behaviour. The relevant risk information is attached to this agent. In accordance to the system science, an activity agent possesses all the elements that can be seen in the IDEFO approach. Firstly, relevant resources and methods used are mapped. Divided by its type, resources are represented as agents and methods as values (see 2 and 3 in Figure 2.6). The resource agent includes the equipment and all the actors, external and internal, included in the process. Resource-related factors are directly connected to the corresponding agent and they can evolve based on agent behaviour. These factors are more aleatory than epistemic.



Figure 2.6 Activity model

Inputs (see 4 in Figure 2.6) and controls (see 5 in Figure 2.6) are represented as risk factors. Consequently, they hold a value between 0 and 1 indicating their quality. Value 0 means no issues and value 1 means high quality issues. As an example, if the definition of design requirement, the companies can use market research. In this case, market research represents an input for the requirements definition. Hence, the quality of this study directly impacts the design. Considering this

information, the input value can be set in [0, 1] depending on the comparison between the expected and achieved study. Similar can be stated for controls. The design is usually led by appropriate standards. If it is considered that the standard based on which the design is conducted is going to pass through the changes during the development process, its value can be set accordingly.

The inputs and controls can be independent or dependent on the development process. Independent inputs and controls are not process-related. They come from the external environment. They include standards, any analysis or surveys not conducted within the development process. Hence, their control is highly limited and judgement more epistemic than aleatory. Previously conducted analysis, design of the component in the assembly or a market research conducted by the company are the examples of dependent inputs and controls. Their value is the result of the interactions and relations of the previously conducted activities. Hence, they can't be modelled solely as aleatory but need to take into account interaction uncertainty. For this reason, dependencies between and within the tasks need to be modelled.

The dependencies between tasks can be categorized as pooled, sequential and reciprocal (Jin & Levitt, 1996). The agent-based modelling enables to capture pooled relationships due to the representation of resources of the development process. The input or control dependency on the output of a previously conducted task is the example of the sequential dependency. This sequential dependence is represented in the developed model. Also, the model can take into account the task sensitivity. Task sensitivity represents how sensitive dependent task is to the changes in the input task (Yassine, 2007). This representation is enabled using agent-based model and the risk behaviour model that is to be detailed in the following part of this section. The reciprocal dependency where task can be conducted in parallel but need to share some information is just implicitly captured in this model. These relations are the result of the connections within the product of design and hence they can be visualized better in the product level. Hence, they are covered in greater detail in Chapter 3.

To represent sequential dependency, the activity needs to have appropriate outputs (see 6 in Figure 2.6). Users can define their own outputs (and risk factors in general), however, in this work, it is considered that cost, time and value risk can be used to represent all the desired relations. PMBOK underlines the risk of cost, time, quality and scope as appropriate. This thesis considers the first three, while the scope risk is to be included in the future work. The cost risk is maybe the main decision-making criterion in the project literature. Often all other criteria can be transformed into this one, like it is the case in the cost-based analysis. The time risk enables the representation of sequential relations in terms of time. This enables the model to be directly linked to tools used in project management, like critical path method. The information sequence is shown through the value risk. Value risk represents the performance quality of the task. The dependent activity uses the output value of the previous task as its input.

Once dependencies between tasks have been explained, it is the place to represent the dependencies within a task. The dependencies form task risk behaviour and result in the task output risk using Fuzzy Cognitive Maps (see 7 in Figure 2.6). Fuzzy Cognitive Map is a directed graph whose nodes represent risk factor values (see 8 in Figure 2.6) and weighted arcs quantify the interactions between those factors. Hence, FCM is used to calculate risk severity. And it is that task output risk that propagates further in the development process. Detailed information about the FCM modelling and use is provided in subsection 2.3.1.

The FCM calculates new risk factor values (severities) based on the initial values. Risk factor values represent deviation from the planned ones. For example, the work is planned for average-skilled worker, but it is performed by a low-skill worker. Risk factor value illustrates the difference in skill between average and low. They illustrate the size of the problem. Based on the previous example, the risk factor

value can be low to medium. On the other hand, if the work is planned to be performed by a high-skilled worker and performed by a low-skilled one, the risk factor value would be categorized as high problem. The initial risk factor values are obtained in three ways. If a risk factor is dependent input or control, its initial value depends on the precedence relationships between activities. The output of an input activity directly defines the value. If a risk factor is independent input or control, its value is judged "as is" usually by one or more experts. Lastly, the initial risk factor values depend on risk events. Risk agent (see 9 in Figure 2.6) is used to represent risk events (see 10 in Figure 2.6). Risk events are problems that may occur in the development process. Risk agent is used to gather all the event-related information including different severities and their probabilities. Also, it connects the events with the appropriate risk factor and activity. If the severities depend also on a behaviour of resources and methods, the risk event agent enables this connection. Globally speaking, risk events can be divided into two categories: standard and hazardous. Hazardous events impact directly the output risk, they are epistemic and can be viewed as a "surprise risk". Their probability is not known precisely but is considered low. The effect, on the other hand, can be severe. They are modelled as random events. Standard risk events influence other risk factors. Their probabilities are known, and severities are represented in discrete manner. Since several events can impact the same factor, they can be represented in the form of a network.

The result of the network is the joint likelihood for each previously determined severity. This is modelled using the Bayesian network (see 11 in Figure 2.6). Hence, at the end of the calculation different probabilities can be assigned to risk event severities. It needs to be taken into account that event networks are both factor and activity dependent. This means that not the same network will define the same factor in different activities. For example, the late finish of the previous project affects the availability of designer only in the first tasks of the observed development process. In case there is no data to model Bayesian network, the probabilities (and severities) can be assigned based on expert opinion. Also, the model can be used for "what if" analysis or to determine the activity or process resilience by investigating the change in outputs with the change in values of different risk factors.

#### 2.3.1. Severity calculation

The calculation of task output risk is performed using Fuzzy Cognitive Maps. This subsection aims at explaining how this calculation is performed and how it impacts the scientific questions.

Fuzzy Cognitive Maps belong to the group of Axelrod's (1976) Cognitive Maps. Developed by Kosko (1986), Fuzzy Cognitive Maps aim to not only represent, but to calculate influence of the causal reasoning. Causal reasoning is initially developed for qualitative purposes; hence the causality represents the expert's interpretation of the reality. Since its initial creation, Fuzzy Cognitive Maps have been adapted multiple times. Thus, in this section the form used in the thesis is explained.

FCM is a cyclic signed directed graph. Like any other graph it is made of nodes and, in this case, weighted links. Contrary to its initial definition, the values of the nodes are not limited to 0 ("off") and 1 ("on"). They are defined in a range [0, 1]. Value 0 indicates no risk, while 1 indicates high risk. This implies that all the real-world values are firstly normalized in order to be used in FCM. After the calculation, denormalization is performed to obtain real risk outputs. The relationships between the nodes can be positive or negative, ranging [-1, 1]. Positive relation means that the two factors are moving in the same direction i.e. if the parent node is increasing/decreasing the child node would do the same. Negative weight implies the change in the opposite directions. It should be taken into account that the links are not reciprocal. For example,  $w_{17}$  in Figure 2.6 indicates that the node 1 influences node 7. The reciprocal connection is not included and node 7 has no influence on node 1. In order to

provide this influence, a new link,  $w_{71}$ , needs to be made. For a map to be FCM, two main conditions need to be met (Kosko, 1986): firstly, relationships between the nodes are fuzzy and not only represented by a sign; secondly, the system needs to include feedback loop which introduces a temporal aspect and makes it dynamic. Due to the fact that each link represents independent influence between the nodes, they can be easily removed or added without impacting the rest of the map. However, this implies that this modelling can't take into account the joint effect of nodes (Joao Paulo Carvalho, 2013).

FCM has a second representation in form of a vector and a matrix. Vector is used to represent initial values of risk factors, while matrix is used to represent the relationships between the nodes. Figure 2.7 illustrates this mathematical representation of FCM represented in Figure 2.6. Influence of a factor on other nodes can be seen in the rows, while parent nodes of the observed factor can be seen in the column. In Figure 2.7 this is illustrated for node 1. The output is given as a vector of the n<sup>th</sup> iteration.

$$InputVector = \begin{bmatrix} V_1 & V_2 & V_3 & V_4 & V_5 & V_6 & V_7 & V_8 \end{bmatrix}$$

Others influence 1	$\downarrow$								
1 influences the others $\rightarrow$	0٦	0	0	0	0	0	<i>w</i> <sub>17</sub>	ן 0	
	0	0	0	0	W <sub>25</sub>	0	W <sub>27</sub>	0	
	0	0	0	0	W <sub>35</sub>	0	0	0	
ECM -	0	w <sub>42</sub>	0	0	0	<i>w</i> <sub>46</sub>	0	0	
1 CM =	0	0	0	$W_{54}$	0	w <sub>56</sub>	$W_{57}$	w <sub>58</sub>	
	0	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	0	
	LO	0	0	0	0	0	0	0 ]	

 $OtputVector = \begin{bmatrix} V_1^n & V_2^n & V_3^n & V_4^n & V_5^n & V_6^n & V_7^n & V_8^n \end{bmatrix}$ 

#### Figure 2.7 FCM mathematical representation and meaning

The calculation of new risk factor values is an iterative process based on linear algebra. The following equation is used for calculation:

$$\forall j \in \{1, \cdots, n\}, C_j(t+1) = f\left(\sum_{i=1}^n w_{ij} \times C_i(t) + C_j(t)\right)$$
(2.1)

Here,  $C_j(t + 1)$  represents the value of risk factor in the current iteration;  $w_{ij}$  is the value of corresponding weight;  $C_i(t)$  value of the risk factor currently involved in the calculation; and  $C_j(t)$  value of observed risk factor in the previous iteration. Function f(x) is a sigmoid function, used for its monotony and capability to represent the results between 0 and 1:

$$f(x) = \frac{1}{1 + e^{-kx}}$$
(2.2)

where k is a real positive number determining the steepness. It is often equal to 1.

As it can be seen, the calculation enables all the risk factors to be updated (see OutputVector in Figure 2.7). This implies that output risks are just risk factors of a special interest. Hence, in order to be represented they must be part of the input (and consequently output) vector. The calculation process is iterative and can lead to one of the following conditions (Dickerson & Kosko, 1996): fixed point, limit cycle or torus and chaotic attractor. The system may have a global fixed point meaning that only one

global rule exists and that different inputs will lead to the same stable state. Also, the condition of what state will the system have depended on the size of the attractor region. Hence, the observed system can have multiple attractor regions and types. This means that, depending on the initial conditions, the system may reach different states.

In the context of risk management, this implies that different states on the task level and on the process level can be reached. Also, temporally, the final states may or may not be reached when performing the task. Hence, this broadens the possibility for the analysis of development system behaviour.

As it can be concluded from its definition, FCM and neural networks are closely related. They can be described as a class of discrete time recurrent irregular neural network (Joao Paulo Carvalho, 2013). Without the feedback loops FCM would be discrete feedforward neural network with bias equal to 0 (Joao Paulo Carvalho, 2013). They also share some similarities with qualitative system dynamics that can be applied in the qualitative sense. However, in a case when it's hard or even impossible to represent the system using stocks and flows, FCM can be applied with more ease (Mendoza & Prabhu, 2006). They can be adapted to meet Bayesian network in Bayesian causal maps (Liu, 2001; Nadkarni & Shenoy, 2001).

Sometimes judged as not being really fuzzy, not taking temporal aspect into account or not always matching the stability of a real-world problems, Fuzzy Cognitive Maps have been adapted in its rulebased form or personalized form (João Paulo Carvalho & Tomé, 1999; J.P. Carvalho & Tome, 2001, 2002, 2000; Yaman & Polat, 2009). Also, different literature investigates manner of representing collective knowledge (Gray et al., 2014; Jetter & Kok, 2014) and the learning possibilities similar to those in neural networks (E.I. Papageorgiou et al., 2004; Elpiniki I. Papageorgiou, 2012; Stach et al., 2005). Hence, their usage can further evolve in the context of risk management modelling to meet the desires of the particular users.

As a conclusion, maybe the biggest strength of this method lies in its flexibility: flexibility to transform into another methods based on the available information (rules, Bayesian, system dynamic); flexibility to combine the knowledge of methods that are more experimented and used in practice (neural network); flexibility to adapt to the available knowledge and preference (learning and knowledge representation). Although in the thesis its so-called standard form is applied, the model can be adapted to implement the specific rules if the user desires. The reason why this option is initially left out is the size of the leap between the current risk management approaches and the proposed one. Currently, this approach is not yet listed in the standard. The scientific community is aiming at using this approach on the global, project level that might be hard to interpret and model from the user perspective. Hence, the goal of this work is to provide a first step towards bottom-up approach and to enable further development based on needs, desires and information. This is why FCM are considered as perfect candidate and applied in the previously described form.

# 2.3.2.Likelihood calculation

Fuzzy Cognitive Maps can't be used to calculate likelihood of a risk factor value or the final process risk. For this reason, other methods are used.

Firstly, likelihood is calculated using Bayesian networks. Bayesian network is an acyclic directed graph that is used to explicitly describe direct dependencies between the set of variables (Fenton & Neil, 2012). In the thesis, the nodes in the Bayesian network represent risk events (variables) and the arc is used to indicate directly dependent variable. The relationship is quantified using the conditional probability distribution. The value of the child node directly depends on its parent(s) nodes. Hence, this approach is used to calculate the initial probabilities of risk factor values. Each risk factor has a set of

possible values and which one has greater probability of being activated depends on the risk events. Hence, risk events form Bayesian network that uses Bayesian statistic to provide information on full joint probability distribution but also marginalization with or without evidence. The second one is clearly more used in the context of determination of probabilities of individual values of risk factors. Further information on Bayesian networks in the context of risk management can be found in (Fenton & Neil, 2012; *Risk Management – Risk Assessment Techniques Management Du Risque – Techniques d'appréciation Du Risque*, 2019).

Second way the likelihood is calculated is using Monte Carlo (MC) simulation. The question that can be asked is how MC is used in the context of the thesis. To answer this question, two aspects need to be observed. Firstly, for each value of risk factors probabilities are assigned using Bayesian Networks. Hence, during each run the value of risk factor is obtained randomly based on the obtained distribution. Secondly, Fuzzy Cognitive Maps are used to calculate risk severities. If the system has one global fixed point, the results will always be the same. If it is assumed that each time calculation is performed until stable state is reached and there is more than one fix point state, different simulation runs will give different results. Also, in the context of the temporal aspect, it can be assumed that not all the activities will reach the stable state. Hence, the severity results on task level and hence on the process level highly depend on the initial (randomly) set risk factor value. In this situation, having information about the different possible effect without the corresponding probabilities is considered unsatisfactory. Hence, MC is used to obtain these probabilities by considering aleatory uncertainty of the risk factor values.

# 2.4. Conclusion on the proposed framework and model for risk management solution in a development process

The framework and the model proposed in this chapter aims at separating external causes of risks from the internal risk behaviour. The external events causing the change in the development process are considered as epistemic uncertainty whose behaviour we might never know for sure. For this reason they are modelled separately in two ways: firstly using Bayesian network is sufficient information is available and secondly using expert judgment if those are not.

No matter the data on particular risk event, it is necessary to know ourselves to expect the good outcomes. Hence, the second part of the proposed framework and the model is focusing on internal risk behaviour. Behaviour is usually represented as purely aleatory uncertainty. However, this separation is not considered sufficient for the observed problem. In both cases, in external causes and internal risk behaviour, the solution is also dealing with interaction uncertainty. This type of uncertainty is considered to be one of the leading causes of surprise risk in complex systems.

Three different types of interactions are represented in this framework: interactions between the external events, interactions between the factors of the risk behaviour and interactions between different tasks of the development process. The illustration of the two-task process is presented in Figure 2.8. The first interaction is modelled using Bayesian networks (see 1 in Figure 2.8), second one using Fuzzy Cognitive Maps (see 2 in Figure 2.8) and the last one depends on the sequential relations established in the agent-based model (see 3 in Figure 2.8).

Contrary to the solutions identified in the literature, the presented model is comprehensive. It enables calculation of both likelihood and severity. Likelihood is included in Bayesian networks and Monte Carlo simulation. Calculation of severity is based on the Fuzzy Cognitive Maps. Application of this method enables to represent different grades of the risk behaviour: from stable states to chaotic behaviour.



Figure 2.8 Illustration of a two-task process with its risk interactions and the proposed model

Compared to other FCM approaches, this solution is wrapped-up in an agent environment to enable bottom-up calculation and representation of risk. In literature resources, this model is used mainly on the higher level. The problem with the process (or higher level) modelling of risk lies in the representation and identification of relations. On such an abstract level, is hard to actually explain relations with enough confidence. On the task level or, as we like to call it hands-on-problem level, the problems and risk are happening and hence they can be represented and identified by the experience of all actors involved in the development process. When representing risk on the process level, the question is who is the one representing it or what is exactly represented. With bottom-up approach, there is no such doubt because all the risks can be directly related to different task aspect. From this level, a process risk is calculated through the emergence of tasks.

It is believed that this manner of modelling provides more confidence in risk evaluation by giving context to risk management. Also, the model is flexible and enables different "what if" studies to be executed.

Lastly, due to the use of FCM, the model has a possibility to be adapted in different directions: toward more sophisticated rules, learning from the data, more focusing on data or more focusing on emergent knowledge from the expert. In that sense, the thesis work presents just a first step toward comprehensive risk management in development process. The solution is to grow and adapt based on the available information, user preference and the scientific advances.

# 3. Risk management in a development process – software solution development

Defining a general model is one step forward a software solution, but still several other steps are needed in order to make the simulator. This section covers those steps and explains in detail how software model is organized. It covers general software organization, structure of a model and its sequences.

#### 3.1. General software organization

Guided by the general idea, the model can be divided into two parts: model external (causal) risk events and internal (risk behaviour) model. This connection is illustrated in Figure 2.9.



Figure 2.9 General software organization

As it can be seen in Figure 2.9, external events are modelled in the software dedicated to the Bayesian Networks (BN). In this software all the networks related to different risk factors can be represented. The results obtained from this software are stored in the database for the use of the main part of the simulator. The main software solution is based on agent-based modelling (ABM). Hence, the development tool should be the one supporting agent-based methodology. Risk behaviour and task with all its elements and connections are modelled in this tool. The information about probabilities of different factors is obtained through the database queries. It is considered that, at this moment, the connection between BN software, database and ABM tool is static. This means that if new events are added in Bayesian Network, after all the changes performed in this software, probabilities needs to be updated in the database and then the ABM software can use it. This process is not performed automatically. The simulation can't be executed during the database update. However, this is currently not considered as limitation. Risk models are based on the studiously collected data and their update is not on a daily basis. Also, the model is made to predict the risk based on the previous experience, hence it is considered that the data doesn't need to be updated during the simulation run. If, by any chance, one needs to establish dynamic connection this only implies that the development tools need to be observed from the aspect of their compatibility.

In the thesis, UnBBayes (*UnBBayes - The UnBBayes Site*) is used for modelling of Bayesian Networks, Excel to store data and AnyLogic (*AnyLogic*) for multi-agent simulation. UnBBayes is academically developed open-source solution for BN modelling. It answers to all the needs and it is even written in Java which provides perfect compatibility with AnyLogic. Since BN are used "as is" and since no further development is needed in this part, the tool is directly used any time the network of events needs to be modelled. The main model is made using agent-based methodology; hence, agent tool is chosen with more specific criteria. AnyLogic enables agent, system dynamic and discrete event modelling. It provides great freedom in personalization through the coding interfaces and enables connection with the database in the form of Excel spreadsheets. Hence, it is considered as optimal choice for development software.

The software development can also be performed in other development tools based on the details provided in the following subsections. Hence, the choice made here is not an obligation, but a preference based on the mentioned reasons.

The central element around which the whole model is built is an activity. Activity is an agent (shown with A in Figure 2.10). Hence, it has its own behaviour and it relates to all other agents. Activities can be of different granularity level. Hence, each activity can be decomposed into other subactivities.



Figure 2.10 UML Class diagram of the proposed software solution

# 3.2. Structure of the software model – class diagram

The complete structure of a proposed risk simulator is shown in Figure 2.10. As explained in the previous subsection, the simulator has two parts. The first one is described through Risk event, Bayesian link and Risk network in Figure 2.10 and model in UnBBayes software. The rest of the software is modelled in ABM environment.

Activity possesses also all the elements described in Figure 2.6 and IDFE0 terminology: resources and equipment (organized into Means in Figure 2.10), controls, inputs and outputs. Resources are represented as agents and are further divided into internal and external. The internal ones comprise human resources and equipment. Inputs and controls can be a result of a previous activity. However, they can also be coming out of the observed process and in that case, they are considered external. They are represented as independent values (for input, see Independent value and, for control, see Independent control in Figure 2.10). Each activity consumes it means, uses it inputs and controls to produce the output. Hence, the process plan needs to be defined and to map all the elements to different activities. This step is important for adequate process representation and risk evaluation.

The activity and its elements (resources, methods, inputs and controls) are described using Risk factors. The global (company or process) environment is described using Organization factors and linked to the activity. Output risk is one of the factors as well. Factor value is defined using the Bayesian networks. In Bayesian networks, individual risk events are connected into a network that is used to calculate probabilities of different risk factor severities (see Risk in Figure 2.10). These values are directly assigned to each risk factor.

All factors are activity dependent. This means they are defined for a particular activity. It is, however, case that activities share the same risk factor. For example, different activities use the same standard to perform their task. Control risk is a factor described as quality value and used throughout the process whenever necessary. Risk factors related to resources depend on the activity and on its personal values. This is what is called initial severity of a risk factor. Hence, to obtain current value of the resource-related risk factor, its current parameter value is taken into account together with the problems (see Risk in Figure 2.10). How the risk factor value is calculated may vary, but in a general model, average value is taken. However, it can also be a sum or a minimum or maximum of the values. Factor-specific functions can also be defined. This difference comparing to other activity elements is made due to the fact that resource models are made in various branches of engineering (worker models, equipment modes, to name a few). These models are not often used in risk management. However, in the proposed simulator they can easily be implemented and used together with the risk models.

To form risk behaviour, risk factors are connected with fuzzy links representing weighted arcs in FCM terminology. Factors and their links form Fuzzy Cognitive Map. The map is used to calculate risk factors. As seen in subsection 2.3.1, iterative calculation of FCM updates all risk factors. The calculation is synchronized with activity behaviour. Activity firstly updates the values of all its risk factors (see getFCMparameter() under Activity in Figure 2.10). This procedure includes random selection of a risk factor severity (based on the probabilities obtained in BN) and the inclusion of this value with the personal values of resource agents involved in the activity. After this, the activity executes the calculation of FCM (see callFCM() under Activity in Figure 2.10). As a result, the output risks are known, as well as the updated values of risk factors.

Activity outputs can also be influenced by hazardous events. These events rarely happen, but they can have severe impact on the objectives of the whole development process. Hence, their influence is modelled as a direct effect on output risks. They are activated as random event based on their probabilities. This process is performed after the FCM calculation. The activity uses calculateHazardousEvent() (see methods of Activity class in Figure 2.10) to perform this action.

Once the results are obtained on the task level. The appropriate risk information is then propagated to the connected tasks until the whole process is performed. The propagation is enabled using the sequential connection between activities and the adequate functions (activateNextActivity(), deliverFinishOfActivity() and updateRiskFacors() in Figure 2.10).

#### 3.3. Execution sequences of a software model

The software solution includes several agents and functions coordinate to obtain output risk. In order to fully understand its functioning, it is necessary to be aware of execution sequences. Due to the decentralized structure of the model, it is hard to represent all the actions in one algorithm. Hence, they have been divided into risk sequence, agent behaviour and agent sequence. Their representation is made in form of figures in order to better represent connections with other parts of the solution.

#### 3.3.1.Risk sequence

Risk sequence is illustrated in Figure 2.11.



FCM: Fuzzy Cognitive Map



Risk calculation begins with the definition of initial risk factors values where this is applicable (see 1 in Figure 2.11). As stated in the previous subsection, this initial value represents a personal parameter characteristic for an individual agent. It can be a skill level or equipment availability. The value is described as a size of the problem measured from the parameter value used in the project planning. This value is taken from the database. The database can be filled in automatically (if certain parameters are tracked during development) or it can be filled in by the user. Since the parameter value is usually an average, it can be said that the severity is defined as a deviation from the average. Having in mind that the risk factors are used in FCM calculation, their severities are normalized in a [0, 1] range. Value 0 indicates no problem with the observed parameter and value 1 high problem. The values between these boundaries are set in accordance with the observed issue. This step is performed for all resource agents (internal, external or equipment).

In the second step (see 2 in Figure 2.11), influence of risk events is defined. Risk events are described with probabilities and conditional probabilities and connected in a network based on which different problems impacting risk factors are defined. The network provides probabilities for all risk factor severities. Hence, low, medium and high problems probabilities can be determined. The probabilities for each severity are stored in the database. The factors are divided by activities and the activity elements involved. This step is performed in the Bayesian network software and the values are stored in the database. The user provides and builds appropriate Bayesian network manually. The multi-agent simulator uses the information directly from this database.

In the third step (see 3 in Figure 2.11), the actual risk factors are assigned to each activity. This process includes choice between different severities determined through step 2. The choice is made randomly based on the assigned probabilities. Once this is performed, wherever applicable, this value is joined with the initial risk factor value. The way these two problems will be merged in different manners. In Figure 2.11, they are summed. On the other hand, the mean, min or max can also be chosen as a way to represent these two problems. This process of risk factor assignment is performed for all risk factors influencing the activity. It is necessary to notice that the same process is performed for all activities. This process is performed by activity agent in coordination with other ones.

In the fourth step, activity agent performs risk calculation (see 4 in Figure 2.11). This process is explained in detail in subsection 2.3.1. At the end of this calculation all FCM nodes can change their values. This includes output risks and risk factors. The FCM calculation is followed by the denormalization. This enables to obtain real values for risk outputs. Regarding the other risk factors, the updated value can be assigned as a new initial value of a particular agent. However, this is not always appropriate. For example, through the FCM calculation skill level may deteriorate. This however doesn't imply that the skill of an individual designer has been diminished. This implies only that due to the other factors impacting the activity, the skill level acts lower than it is for the individual worker. Hence, in this case the new skill value shouldn't be equalized with the new individual value of a particular worker. For this reason, in the rest of the thesis, individual risk factors are not updated.

In the step 5 (Figure 2.11) the impact of hazardous event is considered. This event is represented as an agent and whether or not their impact will be taken into account is determined by its probability. This impact of hazardous event is determined in coordination between hazardous risk agent and activity agent. In case the agent is activated, its impact will be directly added to the output risks. The impact is defined directly so denormalization is not required. It should be noted that in the vast majority of cases, this effect will not be taken into account since the probability of these events is extremely low.

#### 3.3.2. Activity sequence

As it can be seen, risk calculation requires involvement of all agents but one of them is of particular importance. This is an activity agent. This agent coordinates all other agents and for this reason it needs to be studied in more detail. The execution sequence for the activity agent is presented in Figure 2.12.



Figure 2.12 Activity agent execution sequence

The activity agent handles different actions. Certain are performed at the agent creation while majority of them are performed while the activity is performed. The first group of tasks will be covered in the agent behaviour part of this section, while the actions performed in the active state are detailed here.

Based on the previous, it is necessary to activate the activity (see 1 in Figure 2.12). The activity is activated in two ways: using the activateActivity() and activateNextActivity() functions. The first function is developed to activate the first activity of the process at the beginning of the simulation. The second activity activates all other activities (on the same level) once all its precedent activities has been performed.

Once the activity is activated, but before any other action, it is necessary to activate child activities if the observed activity is a parent (see 2 in Figure 2.12). This is necessary because all the behaviours and functions related to risk calculations are performed on the lowest level defined. The risk of activities that are based on its child activities is a direct result of these activities. Only the first-order child activities are activated. If the parent is composed of several child activities performed in series, they will be activated once the child activity of the previous order is finished. This activation is performed using previously mentioned activateNextActivity() function.

Once the appropriate activities are activated, the activity is preparing for FCM risk calculation by updating risk factor values (see 3 in Figure 2.12). This process is performed according to steps 1 to 3 of risk sequence (see Figure 2.11). To assign new values, activity agent uses getFCMParameter() function. Using this function risk factors related to independent and dependent inputs and control, methods, resources and organization are defined.

In the fourth step (see 4 in Figure 2.12) risk calculation is performed. This step is the same step as the  $4^{th}$  step of the risk sequence (Figure 2.11). The obtained values are normalized. Hence, in order to obtain actual output risk, denormalization is applied. In the software solution, calculation is based on the stable state or the time frame. If the stable state is not reached after predefined number of iterations, the current state is to be chosen based on iteration limit. However, this situation requires special attention of the user because it indicates either cyclic or chaotic behaviour of the system.

The fifth step (see 5 in Figure 2.12) considers the influence of hazardous event in the same way as explained in risk sequences (step 5 in Figure 2.11). The effect of the hazardous events is defined explicitly, so no additional process is required.

Lastly, when all the calculations are performed and all the output risks are assigned, it is time to finalize the current activity and to activate the next one. Based on the conditions, this process is performed in two ways (see 6 in Figure 2.12). Firstly, in case that the finished activity is not the last activity in the same level, the activity will activate next activity in the same level. This is performed using the previously mentioned activateNextActivity() function. Whether or not the next activity will start depends on all its previous activities. Only when all previous activities are finished, the activity will be activated. Second case that is to be observed is the situation when the finished activity is the last activity in the level. In that case, the activity informs its parent that all child activities have been performed. Since this indicates that the parent activity is finished, it is the parent who will activate the next activity (in the parent level). Again this is performed using the same activateNextActivity() function.

Once the next activity is activated the whole process is repeated.

# 3.3.3. Activity behaviour

Agent performs different actions from the activity sequence depending on the state of its behaviour. This section lists agent states and the corresponding actions performed in each state.

The agent behaviour includes three states: inactive, active and finished. They are illustrated in Figure 2.13.



Figure 2.13 Activity agent behaviour

Once created, all the activity agents are in inactive state. It is at this time that all the connections and basic information from the database are collected. From the database agent saves the information about its parents, previous activities, next activities, resources, risk factors obtained from UnBBayes software and hazardous events linked to it. From this inactive state, agent moves to active state by activateNextActivity() function that delivers activation message. Once in the active state, agent actives child activities, updates risk factors, performs FCM calculation and collect effects of potential hazardous events. Once this is executed, finalization message is delivered. This triggers final risk representation (to include FCM risk results and hazardous events), assignment of the final values after which either a parent is informed that the child activities are finished, or a next activity is activated.

As it can be seen, once in the final state the agent can go back to active state. This is the case when the iteration is necessary. The iteration may be triggered by current activity value risk (that is too low) or by external factors. Entering the active state for the second time may cause different behaviour. In other words, different or pondered FCM can be used. In this standalone development process risk simulator, this step is not performed. However, Chapter 4 includes iterations caused by different events.

# 3.4. Conclusion on software development

The developed software can be divided into two parts: the first part dedicated to the Bayesian network that uses already available solution and the second, central part of the model, that is an agent-based simulator. Illustration of the agent-based simulator is shown in Figure 2.14.



Figure 2.14 Development of the process risk management solution in AnyLogic software

The two solutions are connected using a database that doesn't require permanent link. Together the two solutions provide comprehensive risk management tool. The inclusion of BN software requires certain information, but even if those are not available the simulator can provide both severity and probability

information. Severity is obtained on the task level using coordination between different agents and FCM calculation. Regarding the probability obtained, the only difference is that in the case where no information from BN is available, the probabilities are limited to effect probabilities. The mentioned are obtained by Monte Carlo simulation of the proposed agent-based model.

# 4. Risk management in a development process - solution use

Having a simulator and not clearly define its use, is a waste of resources. As stated in the first chapter, the initial motivation was to develop a solution for risk assessment. Hence, the developed risk simulator is used in the purpose of assessment with the focus on risk evaluation. Thus, the major part of this section aims to answer how the software is used in the context of risk assessment. The decision-making techniques are excluded from the current version of the simulator, but they can be added in the form of separate module. Hence, the second part of this section directly deals with the software use in the context or decision-making and potential extension in this direction.

# 4.1. Risk assessment and the simulator

ISO (*31000: Risk Management — Principles and Guidelines*, 2009) includes three processes in risk assessment: risk identification, risk analysis and risk evaluation. Those three processes in the context of the developed simulator and its use are presented in Figure 2.15.



Figure 2.15 Risk assessment process

Before using the simulator, several steps need to be performed manually. Firstly, risk identification needs to be performed. The aim of this process is to generate comprehensive list of risks (31000: Risk Management — Principles and Guidelines, 2009). In the context of the developed solution, this step includes identification or risk factors. To perform this, user or risk analyst may start form a previous project and the risk documentation, particularly risk register. Risk register is a document listing all the risks with their probabilities and severities if this information is available. Risk register can be obtained using standardized techniques listed in ISO 31010 (Risk Management – Risk Assessment Techniques

*Management Du Risque – Techniques d'appréciation Du Risque*, 2019). Hence, from the methodological point of view the risk identification can remain as it is, but the additional step is required. In order to define risk factors, user must group risks into common categories based on their influence. For example, all the risk events impacting worker's availability will be grouped under the same risk factor. Whether certain group of risk will be defined as risk factor depends also on the limitation in expressing change in this factor, its values or interconnections with other factors. If the user can't evaluate or express any of this, the risk factor shouldn't be included. Instead, risk events should be kept as independent risks.

After identification, risk analysis needs to be performed manually as well. Risk analysis considers causes and sources of risk and their consequences (31000: Risk Management - Principles and Guidelines, 2009). In the context of the developed simulator this process deals with the creation of external event network (Bayesian Network) and Fuzzy Cognitive Map. It is performed in three steps: risk network identification, risk event network identification and risk behaviour definition. Network definition step aims at identifying relationships between previously defined risk factors. This process is again performed by risk analyst using grouping techniques and information from risk register. In other words, in this step, user goes once again through the risk events in risk register. Every time the influence of one risk factor to another has been identified, the link between the risk factor is drawn. Once the whole risk register has been covered and all the relationships between the factors have been noted, the risk event network is to be made. Risk event network is Bayesian Network formed around each risk factor in order to define likelihoods for different severities. These networks define initial values for every risk factor. Same as in previous steps, this network can be created based on risk register and the previously defined risk network. This time, risk event impacting directly particular risk factor are identified and connected into a network. In the third step of risk analysis, the weights are assigned on the previously defined risk network. This process finalizes risk behaviour by completing all the information necessary to build Fuzzy Cognitive Map. With this step it can be stated that the definition of FCM includes identification of risk factors, identification of relations or links between the factors and weigh assignment. Risk analysis is the last manual process performed by the user. Risk evaluation on a task and a process level is performed in the developed simulator.

It shouldn't be forgotten that the manual steps need to be performed for all activity types involved in the development process. Although this might seem as a tedious task, it is necessary to mention that the number of task types is significantly less than the number of actual activities. In Chapter 4, 4 task types are used to describe all the activities identified in design process. It is the combination of these tasks that impacts the final risk. Hence, risk behaviour is a pattern that can be used in different processes. In other words, once these manual tasks are performed for one process they can be reused for other processes.

# 4.2. Information needed

When comes to the utilization of the software, one of the first comments are usually on the availability of information. How the user can provide all this data for the software to run?

Firstly, the discussion can be made on all the development process-data: activity, their resources, methods, inputs, and controls. All this needs to be stored in the proper form in the database for the software to run. And while this form might be a little different from the one the user is currently making; the information is the same. Any project plan contains all this information. Hence, the user or a risk analyst using the proposed simulator needs to fill-in the data tables based on the information from the project plan.

Creating risk behaviour without the proper information might be a bigger challenge. But how does it look to create risk behaviour from risk register? While different resources can be found on risk types and their influences, the question is how to use those resources to make FCM. For this reason, a small illustration is made on how the FCM can be made from available resources. We have used Kendrick's risk decomposition and list of collected risks (Kendrick, 2003) as risk register to create risk behaviour. Starting from the literature resource, the first thing that has been performed is enumeration of risks. In each risk category (schedule, resource, and scope) risks are numbered from 1 until the last risk in the list. Then, all of them have been illustrated in the figure and coloured to make the first grouping. The extract of this process is visible in 1 and 2 in Figure 2.16.



Figure 2.16 Illustration of risk identification and analysis

Here it can be seen that wrong shipment, customer problems and other risks led to the problem with equipment availability which caused late start of the activity. This leads to the identification of two risk factors – equipment availability (see 3 in Figure 2.16) and time (see 4 in Figure 2.16). The similar is done to identify the other risk factors. Hence, the full illustration of Kendrick's risks is shown in Appendix B.1. Although this representation is useful for the risk identification, analysis requires better illustration. Hence, in Appendix B.2 and in the rest of Figure 2.16 the circles and arrows are used to present risk factors and their causes or consequences. The circle represents risk factor. Input arrow represents risk event causing the problem with the observed factor. The numbers in the arrow are the

numbers of Kendirck's risk events. The output arrow indicates that the mentioned risk factor impacts other risk factors based on the risks listed in the arrow. Hence, in 5 in Figure 2.16 the risk influencing the time issues can be seen. They form the link between equipment availability and time because risk 7, 8, 11, 12, 13, 14 are output risks of equipment availability (see 6 and 7 in Figure 2.14). The input risks (see 8 in Figure 2.14) led to the selection of risk to be included in risk event network (see 9 in Figure 2.14). Similarly, risk 7 indicates that time problems can lead to the equipment availability issues, hence the link between time and equipment availability is made (see 10 in Figure 2.14). After this, to finish risk analysis for these two parameters, the expert must assign weights that represent impact of one factor on another.

As it can be seen, the identification and analysis are far from impossible even without detailed resources. The weights can be assigned and tested on a small and simple problem until the behaviour convenes to the experience from previous developments. In case no information is available for BN creation, the list of risks impacting the observed risk factor can be used to judge possible risk severities based on which MC or "what if" analysis of different scenarios can be performed.

# 4.3. Implications on decision-making

The solution is not directly applying decision-making techniques. Instead, the results are presented by category (cost, time and value risk) on task and process level. This enables the user to directly follow the evolution of the development process. However, if need be, due to the highly modular nature of agent-based model separate module with decision making can be added on the current model.

At this moment, the solution provides several possibilities for decision-makers. Firstly, each stakeholder can represent his or hers view through separate FCM. This enables to have calculations for different risk views at the same time. This information can be used to for decision-making. "What if" analysis can be used to test different scenarios. Monte Carlo simulation can be applied to provide probabilities for each scenario but also more globally. In the similar way, variation of risk factor can provide information on system resilience. Lastly, since the solution is based on patterns, decision-makers can test impact of different process configurations on output risks.

# 5. Illustrative example of the proposed solution

After seeing the proposed solution from its idea to the developed simulator, the goal is to verify its utilization through the example that might be seen in practice (Figure 2.17 and Table 2.5).



Figure 2.17 BPMN development process structure of the observed example

# Table 2.5 Development data

			Resource						]	Equip	pment			Me	thod		C	ontrol			Input					
ID	Activity	Project sponsor	Project manager	Fan + motor Lead	Heating unit Lead	Casing, power + control Lead	Vendor	Fan + motor Member	Heating unit Member	Casing, power + control Member	Word	Excel	Mail	Power point	Brainstorming	Solution proposition method	Link & Equivalence method	Choice method	Requirement constraints	Control from previous activities	<b>Requirement</b> information	Scope information	Review requirement information	Input from previous activities	Initial cost	Initial time
1	Kick-off meeting		х	х	х	х	х							х							х				50	5
2	Criteria definition	х	х								х		Х									х			10	3
3	Scope review	х	х								х		х									х			10	3
4	Internal creation																								69	54
5	Initial meeting fan + motor			Х				х			х										x				5	2
6	Initial creation fan + motor			Х				х								Х			х	5	x			5	15	15
7	Review fan + motor			х				х			х												х	6	3	1
8	Initial meeting heating unit				х				х		х										x				5	2
9	Initial creation heating unit				х				х							Х			х	8	x			8	15	15
10	Review heating unit				х				х		х												х	9	3	1
11	Initial meeting casing, power + control					х				х	х										x				5	2
12	Initial creation casing, power + control					х				х						Х			х	11	x			11	15	15
13	Review casing, power + control					х				х	х												х	12	3	1
14	Creation session		х	Х	х	х					х	х			х				х	1	x			7; 10; 13	50	5
15	Creation session + external		х	Х	х	х	х				х	х			х				х	1	х			14	60	5
16	Subsystem link creation																								45	45
17	Link creation fan + motor							х									Х		х	15	x			15	15	15
18	Link creation heating unit								х								Х		х	15	x			15	15	15
19	Link creation casing, power + control									х							Х		х	15	x			15	15	15
20	Equivalence solution creation																								36	36
21	Equivalence creation fan + motor							х									Х		х	15	x			17	12	12
22	Equivalence creation heating unit								х								Х		х	15	x			18	12	12
23	Equivalence creation casing, power + control									х							Х		х	15	x			19	12	12
24	Local validation																								15	6
25	Local validation fan + motor			Х				х			х												х	17; 21	5	2
26	Local validation heating unit				х				Х		х												х	18; 22	5	2
27	Local validation casing, power + control					х				х	х												х	19; 23	5	2
28	Choice		х	Х	Х	х						х						х	Х	23	Х			25; 26; 27	50	5

The small development process has been made. The goal of the process is to develop a new hair dryer. The development is focusing on the proposition of initial solution and its risks. The structure of the development process is shown in Figure 2.17 and in Table 2.5.

The project starts with a general kick-off meeting after which the lead team is performing detailed scope and criteria definition. Lead team includes project sponsor and project manager, while the main or core team includes project manager, group leads, group members and a vendor. After the kick-off meeting, it is the core team who starts working on the solution. The core team is divided into three subgroups: motor and fan group, heating unit group and casing, power and control group. Each group is focusing on the design of the parts for which it is in charge with. The design starts with the creation of initial solution. This is an internal three-step process. Hence, every design group is performing these processes in parallel with the others. After all design groups have perform their task, the general creation session is held with all involved actors. After this meeting, external creation session is held to coordinate internal work with a work performed by a vendor. In this example vendor is in charge of new casing materials. Once this activity is successfully performed, each group is focusing in link creations between the proposed solution and the other units. Design alternatives are created in the next task before the proposition is validated locally within each team. Finally, the choice is made on the process level.

Activities with their external and internal resources, equipment, methods, controls, inputs and initial times and costs are shown in Table 2.5.

The project plan is a document that contains various information about the project including its Gantt chart, project schedule, budget plan and others. The development process structure (Figure 2.17) and the duration of each task in Table 2.5 can be directly defined based on the Gantt chart. Cost information can be taken from the budget information. Activities and their resources are usually presented in the project schedule. Hence, this information can be used to fill-in this information in Table 2.5. The information about the equipment, methods, inputs and controls if not explicitly defined in the project plan can be easily added since they are close related to the subject. Thus, every actor involved in the development process can provide the needed information based on his/her experience.

Process structure (Figure 2.17) and data table (Table 2.5) provide information on sequencing and parentchild relationships between the activities. Temporal sequencing is directly visible on the structure. Information sequencing is defined in the data table through inputs and controls from previous activity. The number in these columns represents ID of the previous activity. The output from the same activity can be used as an input and as a control. The goal of the simulator is not to treat all the outputs of the activities individually, but to focus on their value. Thus, this situation implies only that certain outputs are used as the inputs and others as a control. The example is the output of the activity 15. This activity is a creation session with external vendor and surely it will result in several outputs including technical specification, measures of the product and others. Clearly, not all of them will be used in the same way. Hence, certain are used as an input and others as a control. Parent child relations are indicated firstly in the development process structure using adequate BPMN symbols and further supported in the data table (Table 2.5).

Risk information used for the risk management is based on existing risk registers that the company possesses. In this example, Kendrick's list of risks is used as a risk register. The whole list is used to model risk behaviour (i.e. Fuzzy Cognitive Map). However, since the goal of this example is to illustrate the main model functions and due to the lack of probabilities and severities in the mentioned register, number of risks used to model risk event network (Bayesian network) and hazardous events is limited and presented in the first column of Table 2.6.

Risk description	Risk factor and Activity number where the risk event was included in risk event network
Neophyte project staff lacked technical expertise and required extra training time.	Skill: 6, 9, 12, 17, 18, 19, 21, 22, 23
"Rolling Sledgehammer": The prior project tied up (and exhausted) staff, so the current project started late and slowly.	Availability: 1, 2, 3, 28
The project had funding, but, due to head count limits, no staff was available.	Availability: 1, 2, 3, 28
Needed people were still on a prior project.	Availability: 1, 2, 3, 28
Illness during key project work hit most of the project staff.	Availability: 5, 7, 8, 10, 11, 13, 14, 15, 25, 26, 27
Key staff was lost to a customer "hot site."	Availability: 5, 7, 8, 10, 11, 13, 14, 15, 25, 26, 27
Manufacturing problems diverted project contributors.	Availability: 5, 7, 8, 10, 11, 13, 14, 15, 25, 26, 27
An earthquake made part of the project team unavailable for work.	Availability: 5, 7, 8, 10, 11, 13, 14, 15, 25, 26, 27
Required end-of phase review was delayed	Cost, time and/or value: 28
A move from former location	Cost, time and/or value: 1
An unannounced audit	Cost, time and/or value: 1, 2, 3, 28
Proprietary data were necessary but owners were reluctant to provide them	Cost, time and/or value: 1, 2, 3

Table 2.6 Risk data: Hazardous risks and risk events

Having listed all the information needed, the risk assessment process using the developed methodology and software solution can be presented. Several aspects are discussed: risk identification and analysis, risk evaluation and general conclusion.

#### 5.1. Risk identification and analysis

Risk identification and analysis are manually performed in the same way as explained in Section 4.1 and further elaborated in Section 4.2. Here, instead of explaining it again in details, the whole process is to be covered from the aspect of one risk register entry. The risk event "Rolling Sledgehammer: the prior project tied up (and exhausted) staff, so the current project started late and slowly" available in Table 2.6 will be studied and used in risk identification and analysis. The illustration of the risk identification and analysis is shown in Figure 2.18.

Risk identification starts by finding "keywords" in a risk description that describe risk behaviour. In the case of the observed risks, "tied up staff", "slowly" and "late" describe the system behaviour. These keywords can be directly translated into the following system parameter (see 1 in Figure 2.18). Hence, "tied up staff" is describing the availability of resources. "Slowly" indicates that the performance has not been as planned. "Late" indicated that the product temporal aspects have not been respected. Thus, three factors are identified: availability, performance and time. The time, as emphasized before, is considered as output risk. Identification process has listed the following risk factors: resource availability (A), resource performance (P), resource skill (S), resource motivation (M), external resource reliability (R), external resource quality (Q), equipment availability (EqA), equipment support (EqS), method (Md), control (C), previous control (PC), input (I), previous input (PI), project importance (Imp), project dependency (D), project communication (com), project organization (O) and output risks (time (T), cost (Cost) and value (V)).



Rolling Sledgehammer: The prior project tied up (and exhausted) staff, so the current project started late and slowly

Figure 2.18 Risk identification and analysis based on one risk register entry

After identification of risks, it is time for risk analysis. This process comprises three steps: risk network, risk event network and task behaviour definition. Risk network definition is representing relationships between the risk factors. The example risk states that due to the tied-up staff "the current project started late and slowly". As it can be seen in 2 in Figure 2.18 this directly puts availability of the staff (due to the "tied up staff) in the root of productivity and time issue. This relation, however, can be represented in two ways. Firstly, it can be stated that availability problem causes productivity problem that leads to time issue. Or it can be said that the availability issue leads to productivity and time issues. Both options are presented in 2 in Figure 2.18. Which option will be chosen, depends on the preference of the expert and the modeller. Anyhow, both options can be tested in the tool to see how they impact output risks.

Globally, Figure 2.19 illustrates risk network for the observed problem based on all Kendrick's risks. This map is a general map. Hence, in order to obtain particular map related to the activity, only the elements not involved have to be removed. If, for example, the vendor is not included in the task, its

nodes and corresponding relations have been deleted. In the map presented in Figure 2.19 every risk factor represents the problem. For example, "availability" indicates availability problem. The relationships are, then, determined accordingly. Hence, availability-performance link can be read as: availability issue leads to performance issue.

![](_page_101_Figure_2.jpeg)

Figure 2.19 Risk network (FCM) of the example problem

In the third step (see 3 in Figure 2.18), risk event network is defined. In this process, the causes influencing risk factors are to be determined. The presented risk identifies only one cause leading to availability issue. It is a "rolling sledgehammer". This is the case when late previous project leads to the problems in the current one. Hence, if the Bayesian (risk event) network is to be created based on this risk, the question that needs to be asked is how often the previous project causes the problems in the current ones.

In the presented example, Bayesian networks are created only for risks shown in Table 2.6. Since the goal of the example is illustrative and the probabilities and severities are not represented by Kendrick, the initial information for creation of Bayesian network was missing. Hence, the probabilities and conditional probabilities are set randomly. Thus, the results shouldn't be used as an implication of behaviour of any particular development process. On the other hand, even the random input values illustrate well the solution functionalities.

Figure 2.20 illustrates the creation of one Bayesian network. This availability is used only in first activities of a development process since the risk events related to it are considering influence of the prior project and organizational issues that usually arise at the beginning of the project.

![](_page_102_Figure_1.jpeg)

Figure 2.20 Bayesian network for availability (created in UnBBayes software)

Similar networks are created for other risk factors based on the information presented in Table 2.6.

Table 2.7 provides information on risk factors severities and probabilities for different activities obtained from Bayesian Networks. All the risk factor effects are defined as no problem, low and high problems. The values of problem severities differ from factor to factor. The corresponding probabilities are assigned for all of them.

Table 2.7 Severities and probabilities of different risk factor values based on the risk event networks form Table 2.6

Risk factor and Activity number	Low problem value	High problem value	<b>Probability</b> low	Probability high
Skill: 6, 9, 12, 17, 18, 19, 21, 22, 23	0.15	0.45	0.426	0.21
Availability: 1, 2, 3, 28	0.3	0.7	0.574	0.401
Availability: 5, 7, 8, 10, 11, 13, 14, 15, 25, 26, 27	0.3	0.6	0.454	0.166

Risks considered as hazardous events and their probabilities and effects are shown in Table 2.8. These risks directly influence output risks. The probabilities and severities shown in the table are assigned randomly since no real data was provided by Kendrick. They are modelled as random events.

Hazardous event	Activity	Probability	Cost effect	Time effect	Value effect
Required end-of phase review was delayed	28	0.05	0	15	0
A move from former location	1	0.06	18	5	0
An unannounced audit	1, 2, 3, 28	0.07	0	20	0
Proprietary data were necessary but owners were reluctant to provide them	1, 2, 3	0.05	0	10	0.9

Table 2.8 Hazardous risks: their probability and effects

Lastly, in the fourth step (see 4 in Figure 2.18) the weights are to be added on the relations between risk factors. These weights are to be determined based on the expertise of project actors, modeller and previously defined steps. Since the goal of this example is purely illustrative the weights are assigned randomly.

The general FCM matrix for the observed example is hence presented in Figure 2.21. As it can be seen in the figure, the FCM matrix is based on the identified factors and the risk network (Figure 2.19). Row and column order of the matrix corresponds to the input/output vectors. Rows show the influence of the observed risk factor on other factors (see "availability (A) influence on others" in Figure 2.21). Columns represent the influence of other factors on the observed factor (see "others influence availability (A)" in Figure 2.21). In the same way the second column list the factors influencing performance and so on.

InputVector = [A P S M R Q EqA EqS Md C PC I PI Imp D Com O T Cost V]

Others influence availability (A)	1																			
Availability (A) influence on others $\rightarrow$	Γ0	0.9	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3
	0	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0.9	0	0
	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8
	0.1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0
	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6
FCM =	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5
1 0.4 -	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5
	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7
	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0
	0.7	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0.5	0	0	0	0
	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3
	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9
	0.4	0.2	0	0.1	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0.8	0.15
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	LO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0	0

 $Output Vector = \begin{bmatrix} A^n & P^n & S^n & M^n & R^n & Q^n & EqA^n & EqS^n & Md^n & C^n & PC^n & I^n & PI^n & Imp^n & D^n & Com^n & O^n & T^n & Cost^n & V^n \end{bmatrix}$ 

#### Figure 2.21 FCM of the presented example

In order to obtained matrix of a particular development process activity, only rows and columns associated to the actor not involved are to be removed. This is a direct consequence of the characteristics of FCM explained in section 2.3.1. Since, all relationships are based solely on the factors creating the relationships, the removal of rows and columns does not impact the other factors of the system.

Creation of the matrix is the last step of risk analysis and the last manual step. As stated before, this process might seem tedious, but the obtained matrices and risk event networks can be reused in different development processes. Also, if need be, task behaviour adaptation is easy and fast. Hence, after initial analysis of a system, the information obtained can be adapted to fit different needs. These matrices can also be used to represent different views of stakeholders. Since the model is activity-based, even the actors that were not usually involved in risk management can now participate, express their point of view and use the results obtained from the analysis to gain better understanding of the behaviour of their activities. Hence, even before the actual evaluation, the view of the system risks can be improved using the proposed methodology. The next section illustrates risk evaluation based on the developed simulator. This step provides quantification of the risks listed in risk identification and analysis.

#### 5.2. Risk evaluation

Risk evaluation is performed in the developed simulator. The risk prediction is performed firstly on the task level and secondly on the process level. The main tool uses the database information containing information about the development process and the data on risks obtained from UniBBayes software. The results include cost, time and value risks for each activity. The process cost is calculated as a sum

of individual cost. For the time risk, each individual activity keeps track of its actual start and end time based on the accounted risks. Hence, the end time of the last activity represent the process end time. The individual values are included in the next activities through sequential relationships and task behaviour. Thus, the current activity shows the overall process value.

The information used for the simulation has been shown in section 5.1. However, one more group of parameters has been defined to enable more realistic risk analysis. The initial risk factor values for all the resources, equipment, methods, controls and inputs have been defined. They are all presented in Table 2.9. In terms of resources, these values represent individual skill, availability, performance and motivation level for each internal actor involved in the development. Similar can be stated for the risk factors from other groups.

Value 0 indicates that there is no problem in the observed aspect comparing to the planning. The closer the value gets to 1, the bigger the problem is. It is on these initial values that the risks from Bayesian Networks are either added or their influence is judged based on the mean value, maximum or minimum values. Hence, the solution directly considers the state of the system and the risk events influences on the system. The results are shown in Tables 2.10, 2.11 and 2.12.

Table 2.10 shows the actual cost, time and value for each activity obtained during one simulation run. The results are based on the achieved stable state for each activity. Having in mind that the nature of this example is purely illustrative and not based on the real development process, the detailed analysis of the system behaviour will not be made. However, certain details need to be analysed.

The risk effects are highly problematic comparing to the initial cost, time and value. If this is not what the user has expected, the weight of the FCM can be adjusted to reach the expected output values. The recommendation is hence to test simpler cases until the weights are set. Then the task behaviour can be applied on more complicated problems where the results are not obvious.

All the activities are using the same global FCM. Only the elements (vendors, controls, etc) not involved in the task have been removed. All other weights are the same in all activities. The initial values, risk networks and hazardous events vary based on the activities (see tables 2.7, 2.8 and 2.9). The variation is also made based on the range of effect. For example, activities #2 and #3 use the same FCM but the time effect for the first one ranges from 0 to 25 time units and for the second one from 0 to 13 time units. This is the main reason why different results have been obtained. However, certain activities tend to have the same results. For example, activities #17, #18 and #19 have the same effect range and hence all their values are the same although different actors have performed the tasks.

To further analyse this behaviour, the unnormalized output vectors are shown in Table 2.11. All the activities having identical FCMs are coloured in the same colours. Here, it is clear that all the activities sharing the same Fuzzy Cognitive Map have reached the same fixed point. Without going into further details, this may indicate that the system has a global fixed point or that the conditions represented in the example lead to the same fixed point. Variation of the risk factors can illustrate all the states that the system can reach.

				I	Resour	rce					Equij	pmer	ıt		Me	thod		C	ontrol			Input	
Initial risk factor value	Project sponsor	Project manager	Fan + motor Lead	Heating unit Lead	Casing, power + control Lead	Vendor	Fan + motor Member	Heating unit Member	Casing, power + control Member	Word	Excel	Mail	Power point	Brainstorming	Solution proposition method	Link & Equivalence method	Choice method	<b>Requirement</b> constraints	Control from previous activities	<b>Requirement</b> information	Scope information	Review requirement information	Input from previous activities
Skill	0	0	0.1	0	0		0.5	0	0														
Availability	0.5	0	0.5	0.2	0.1		0	0.1	0														
Performance	0	0	0	0	0.3		0	0.2	0														
Motivation	0	0	0	0	0		0	0	0														
Vendor reliability						0.1																	
Vendor quality						0.5				1				Ì									
Equipment availability										0	0	0	0										
Equipment support										0.05	0.05	0.1	0.05										
Method value														0.05	0.5	0.3	0.2						
Control value																		0.9					
Input value																				0.9	0.95	0.98	

#### Table 2.9 Risk factor initial values for resources, equipment, methods, controls and inputs

Table 2.10 Obtained results from one simulation run

Activity ID->	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Initial cost	50	10	10		5	15	3	5	15	3	5	15	3	50
Actual cost	63.662	0.027	18.807		7.489	19.146	5.489	7.489	19.146	5.489	7.489	19.146	5.489	66.766
Initial time	5	3	3		2	15	1	2	15	1	2	15	1	5
Actual time	24.379	26.592	15.296		6.707	24.384	3.824	6.707	24.384	3.824	6.707	24.384	3.824	19.202
Initial value	1	1	1		1	1	1	1	1	1	1	1	1	1
Actual value	0.025	0.027	0.027		0.027	0.012	0.027	0.027	0.012	0.027	0.027	0.012	0.027	0.007

Activity ID->	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Initial cost	60		15	15	15		12	12	12		5	5	5	50
Actual cost	101.823		19.146	19.146	19.146		12.829	12.829	12.829		5.415	5.415	5.415	68.426
Initial time	5		15	15	15		12	12	12		2	2	2	5
Actual time	29.245		26.26	26.26	26.26		16.692	16.692	16.692		3.941	3.941	3.941	21.088
Initial value	1		1	1	1		1	1	1		1	1	1	1
Actual value	0.004		0.012	0.012	0.012		0.012	0.012	0.012		0.027	0.027	0.027	0.007

Activity ID	Α	Р	S	Μ	R	Q	EqA	EqS	Md	С	PC	Ι	PI	Imp	D	Com	0	Т	Cost	V
1	0.856	0.974	0.706	0.815	0.659	0.659	0.813	0.659				0.659		0.659	0.659	0.788	0.746	0.967	0.833	0.975
2	0.855	0.983	0.706	0.816			0.812	0.659				0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
3	0.855	0.983	0.706	0.816			0.812	0.659				0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
5	0.855	0.983	0.706	0.816			0.812	0.659				0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
6	0.855	0.995	0.706	0.817					0.659	0.659	0.659	0.659	0.659	0.659	0.659		0.746	0.938	0.829	0.988
7	0.855	0.983	0.706	0.816			0.812	0.659				0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
8	0.855	0.983	0.706	0.816			0.812	0.659		_		0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
9	0.855	0.995	0.706	0.817					0.659	0.659	0.659	0.659	0.659	0.659	0.659		0.746	0.938	0.829	0.988
10	0.855	0.983	0.706	0.816			0.812	0.659				0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
11	0.855	0.983	0.706	0.816			0.812	0.659				0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
12	0.855	0.995	0.706	0.817					0.659	0.659	0.659	0.659	0.659	0.659	0.659		0.746	0.938	0.829	0.988
13	0.855	0.983	0.706	0.816			0.812	0.659		-		0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
14	0.855	0.996	0.706	0.817		-	0.812	0.659	0.659	0.659	0.659	0.659	0.659	0.659	0.659	0.789	0.746	0.943	0.83	0.993
15	0.857	0.996	0.706	0.817	0.659	0.659	0.813	0.659	0.659	0.659	0.659	0.659	0.659	0.659	0.659	0.789	0.746	0.969	0.833	0.996
17	0.855	0.995	0.706	0.817					0.659	0.659	0.659	0.659	0.659	0.659	0.659		0.746	0.938	0.829	0.988
18	0.855	0.995	0.706	0.817					0.659	0.659	0.659	0.659	0.659	0.659	0.659		0.746	0.938	0.829	0.988
19	0.855	0.995	0.706	0.817					0.659	0.659	0.659	0.659	0.659	0.659	0.659		0.746	0.938	0.829	0.988
21	0.855	0.995	0.706	0.817					0.659	0.659	0.659	0.659	0.659	0.659	0.659		0.746	0.938	0.829	0.988
22	0.855	0.995	0.706	0.817					0.659	0.659	0.659	0.659	0.659	0.659	0.659		0.746	0.938	0.829	0.988
23	0.855	0.995	0.706	0.817					0.659	0.659	0.659	0.659	0.659	0.659	0.659		0.746	0.938	0.829	0.988
25	0.855	0.983	0.706	0.816			0.812	0.659				0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
26	0.855	0.983	0.706	0.816			0.812	0.659				0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
27	0.855	0.983	0.706	0.816			0.812	0.659				0.659	0.659	0.659	0.659	0.788	0.746	0.941	0.83	0.973
28	0.855	0.996	0.706	0.817			0.812	0.659	0.659	0.659	0.659	0.659	0.659	0.659	0.659	0.789	0.746	0.943	0.83	0.993

#### Table 2.11 Obtained output vectors from one simulation run

Table 2.12 Obtained results from MC simulation for activity #14

Activity 14	Mean	Deviation	Samples values	Number of samples
			0.991	13
Value	0.993	$2.41*10^{-4}$	0.992	67
			0.993	920
			0.808	37
Cost	0.820	0.004	0.826	57
Cost	0.829	0.004	0.829	25
			0.83	881
Time	0.042	5 992*10-4	0.94	37
1 mile	0.945	5.002.10	0.943	963

However, these are the results obtained just based on one simulation run. To investigate if this stable state is reached under different conditions, Monte Carlo simulation has been performed. The output risks of the same activity have been followed during 1000 runs. This number of runs is considered sufficient having in mind that no error has been set in this illustrative example. The activity has reached the fixed point in all the runs and its time, cost and value risk have been the same in all runs (0.943, 0.83 and 0.993 are the unnormalized values for time, cost and value respectively).

The same experiment has been performed with the random FCM iteration number. Iteration number have been uniformly distributed between 1 and 27. The upper boundary have been set while having in mind that the stable state is usually reached in 26 iterations. The obtained results are presented in Table 2.12. The results confirm that FCM converges fast towards its fixed point. This is implied since the same fixed point is reached in great number of runs no matter the limitation in the number of iterations.

Finally, it can be concluded that the developed tool can represent different states of the system. By analysing effects of different initial conditions and risks included, the resilience of the development process can be studied. It can also be said that the same fixed points can cause the effect that seem different due to their initial effect magnitude. Hence, it is interesting to investigate the core of each effect. As it has been shown in this illustrative example, all these analyses can be performed in the simulator. Hence, the solution is comprehensive and enables its user to make a step forward better understanding of risk behaviour.

# 5.3. Conclusion on the tool use

Illustrative example presented in this section has shown the capabilities of the proposed methodology and the corresponding simulator. The author has taken the user role and performed all the experiments. In short it can be stated that the solution sets risk management in the context of the development process. While the mentioned will be covered in detail in the conclusion of this chapter (Section 6), several ideas have been confirmed through the presented example. Firstly, through identification and analysis it has been shown that the current approaches can be adapted to present risks with more context. Epistemic risk events can be divided from the aleatory and interaction-related nature of the system. This way, users are not observing risk as the forest of random events. Instead, they are building their knowledge and they can clearly distinguish what is known for them and what is not. Once this is performed, using the developed simulator, the user is capable to quantify its current knowledge about the development process. This results in different behavioural analyses that may or may not include unknown individual events.

# 6. Risk management in a development process – conclusions on the performed work

In this chapter, the comprehensive risk management solution has been presented from its initial idea to the application using the developed methodology and simulator. This approach has focused only on development process risks. The main idea is to separate unknown individual events from risk behaviour of the observed system. In both cases, the interactions are explicitly considered which is only seldom present in the current literature. Risk events impact system parameters and that is how individual risk propagates in the development process. Those events and their interactions are modelled based on the available data in form of risk event networks (Bayesian networks). The interaction within the system are modelled through the relationships between the development tasks. The interactions of risk events,
actors, equipment, methods and information leads to the systemic view on the development process risk.

From the user perspective, the proposed methodology and simulator remain close to the current risk management approaches enabling the transition from traditional to more systemic risk view. The steps performed manually by the user are related to the standard documentation: risk register and project plan. The steps that are needed to make transition between these documents to the simulator are thoroughly explained. The main advantage is that the mapping of information is made on the task level. Hence, the user doesn't need to have global knowledge on the process risk but rather to focus on his (hands on) experience and to apply it on the task where he is directly involved. After this is done, it is the developed simulator that provides prediction of risk on task and process levels. Different behaviours can be studied using the proposed solution including stable states, chaos or resilience.

Having all the previously mentioned in mind, the main contributions can be summarized as follows:

- The comprehensive solution is provided for risk interactions in the development process.
- Risk events are separated from risk behaviour enabling statistical and systemic view on risks.
- Rather than focusing on determining only probabilities or effect, the solution enables both effect and probability calculation. Effect includes nuances between stable and chaotic states while combination of Bayesian network and Monte Carlo simulation is used to represent probabilities of different events and effects.
- Since the risk is modelled on a task level, the solution provides the mean for bottom-up integration of risk. Thus, the user with the hands-on development can directly participate in risk management.
- The solution can be used a pattern for different development processes.
- The simulator enables "what if" multi-path and multi-view analysis.

The solution also has certain limitations that leave the possibility for further research. The main limitation is that the current model is based on the user experience. Hence, the future work may be oriented towards data collection and application of data mining or artificial intelligence techniques. In terms of risk mitigation and decision-making that were initially out of scope of the thesis, two main improvements can be made. Firstly, risk mitigation can currently be taken into account only if it is modelled using task with their corresponding behaviour. In that sense, the current solution can be extended by applying optimization techniques. Secondly, since one of the ideas was to provide multiview of risk, the decision-making techniques weren't included in the solution. However, since the solution provides detailed results for all risk factors (not only the output risks) on task and process level, decision-making approaches can be directly applied if unidimensional representation of risk is desired. With this in mind, the user can easily make trade-offs between different options in the development process.

After the process risks has been addressed, Chapter 3 presents the solution for product aspects that haven't been considered so far.

# Chapter 3: Operational framework and simulator for product risks in a context of its development

#### Abstract

The third chapter of the thesis focuses on product performance risks. Having in mind the main drivers identified in the literature, the model is focusing on their representation and propagation from one product element to other ones. The main risk factors considered are design task, requirement and technology uncertainties. The idea of the solution is that the risk factors are firstly influencing one particular product element after which through the connections between the product they propagate further into system. Also, in the same way as the problems are propagating, the solution to those problems needs to propagate. Hence, the product performance is dynamically changing due to the drivers influence, problems and solution propagation. In this chapter, the solution is proposed to consider all the mentioned. The development from idea, framework, model to simulator is presented. The proposed solution is based on FBS linkage, modified SIR simulation and agent technology. The main output is risk evaluation and prediction, but other management steps are also addressed. Hence, the presented methodology enables risk analysis that is closer to the designer and the process. The solution is illustrated using an academic example. The results obtained from the simulator include critical component identification, process iteration and performance prediction, among others.

Project manager may say that knowing your project guaranties it's success. However, this is only partially true because each development process has another equally important face – the face of the product. While controlling the development process will surely limit certain risks, leaving the whole product aspect unmanaged can cause a lot of "surprises". If the problem appears in one product component what will be the overall product performance? Further, once the problem and its consequences are identified, what it takes to deal with them? Finally, how all this influences the development process and its related risks?

With these questions in mind, leaving the product unmanaged seems irrational. It looks like leaving one part of yourself unexplored since it's not the place where the enemy will hit. Leaving engineers and designers to deal with the mentioned and to report to management is even more irrational. Although engineers and designers know their product the best, their scope is limited to proper functioning of the final product and not necessarily observing the product risks in the context of the whole development process. Hence, the tools used in product risk management are not necessarily suitable for the assessment of risk for product under development.

The goal of this chapter is, hence, to propose the comprehensive risk management solution for product under development. The risks included are the risks that may be of pure product-origin, but also those caused by the development process. The output is presented in the form of product performance risk. In that sense, the solution can be used standalone or in the merged process-product solution that is covered in Chapter 4.

The chapter is organized in the following manner. The first section deals with the main assumptions related to the product risks and the current state in the literature. In the second section, the framework and the model of the proposed risk management solution are presented. Third section deals with the software development. User perspective is covered in the fourth section. Section 5 illustrates the solution using the academic example of a hair dryer design. The chapter is concluded in section 6.

# **1.** Risk management for product under development: from assumptions to state of the art

Risk management for product under development is not a common view of product risk management. Usually, product risks are observed alone, thorough the safety aspect and failure analyses. In the thesis, however, the product is part of the development process. Paradoxically, from the project perspective, product risks are often considered as is. The project assumes that the product will pass safety controls and that those risks will be handled. What the project needs is the information on where the product is currently on the scale from unsafe to perfect, best possible product. In other words where is the product in the scale form maximum to zero risk by taking into account its configuration, used technology, requirements, the development process and other factors. In order to find the proper solution to answer these needs, this section defines the main assumptions and definitions based on which the solution is proposed. Also, the state of the art with its synthesis is performed to underline the suitable approaches available in the literature.

#### 1.1. Risk management for product under development - the assumptions

In the thesis, the goal of the product risk management is to provide the information on evolution of product risks by taking into account problems related to the product itself but also those from the

development process. This specific problem, hence, requires adequate definition of resulting product risk and the corresponding risk terminology. Hence, this subsection deals with these main assumptions.

# 1.1.1.Assumptions: Performance risk for product under development

At the very beginning, it is necessary to define appropriate product characteristics that are influenced by different risks. These characteristics are the ones whose evolution is to be monitored during the product development. As stated earlier, the solution that we are aiming at is general and suitable for different phases of a product lifecycle with the special attention to the design phase. In the conceptual design phase, detailed structure and behaviour of the product are usually not available. Hence, the product characteristics are determined with this in mind. Also, the information obtained needs to be tailored for management and observed in the context of a development process. Hence, pure safety or failure analysis is not in focus.

With all previously mentioned in mind, it has been decided to define product risk through its performance. The performance in this work is considered globally. It is covering all the characteristic of the product that are affected by the development process and that are considered important. This includes everything from failures to quality. However, the focus is not given to any particular aspect but to all of them at the same time. The definition of performance used in the thesis is the one introduced by Browning (1998): "design performance is defined broadly, including system functionality, capability, reliability, price (or life cycle operating cost), delivery timing, number of features, conformance to specifications, durability, serviceability, aesthetics, perceived quality, size, weight, speed, and other measures."

With this broad definition, it is not possible to have a detailed information about the product performance. This is why, in the thesis and in Browning's works, the performance is represented through the uncertainty. Hence, it can be said that the performance risk is "uncertainty in the ability of a design to meet desired quality criteria" (Tyson R. Browning, 1999). Contrary to Chapter 2 where clear distinction has been made between the effects on objectives and uncertainty, here the effect is uncertainty. In other words, the goal of this model is to evaluate the current state of the product performance throughout the development process. Detailed information about the risk terminology is shown in subsection 1.1.2.

In order to enable this prediction, different drivers and their influence on performance are observed (Tyson R. Browning, 1998, 1999): evaluation processes, time and cost, iterations, approvals, product complexity, risk definition, coupling and technology with its maturity and related knowledge obtained by involved staff. The drivers, their relationships and influence of product performance risk are shown in Figure 3.1.

Although Browning has developed an exhaustive list of drivers influencing performance risk from its development perspective, the software solutions presented in the literature are scarcely related to it. Only certain aspects are considered at the time. Hence, in this work, all the mentioned aspects are taken into account when building a solution. To address all these drivers, certain assumptions have been made.

Although the solution presented in this chapter can be used standalone, the ultimate goal has been to provide global risk management solution (Chapter 4) that is composed of process-related solution (Chapter 2) and product-related solution (Chapter 3). Hence, the drivers presented in Figure 3.1 are considered from the perspective of the developed risk management solution for development processes (Chapter 2).

Globally speaking, the drivers can be directly related to the process or to the product under development. Based on Browning (1998, 1999) and taking into account already developed process model, processrelated drivers are marked in dashed line in Figure 3.1.



Figure 3.1 Drivers influencing product performance risk (based on Browning (1998))

The first driver is *evaluation*. Evaluation is performed to check if the product meets the desired goals (Tyson R. Browning, 1999). All other driver definitions are, as well, based on previously mentioned Browning's works. Factors that are impacting the quality of the evaluation include: design reviews (formal and informal and their frequency), verification and validation testing, communication, coordination and integration quality, and design concept initial quality. The first three groups are purely process related. Hence, in this work they are indirectly considered (see section 2 of Chapter 3). Design concept initial quality depends on *product complexity, product and process novelty, requirements quality, simplicity and stability*. This factor directly impacts the number of iterations that are required for the product to meet the desired goals. Thus, this group of factors will be directly included in the product risk management solution. The *iterations* are not to be known in advance, but to be represented through the iteration productivity. Apart from the mentioned, product performance risk depends on *product complexity and stability, requirements negotiability, product and process novelty and modularity, simplicity and stability, requirements negotiability, product and process novelty and modularity.* The mentioned is directly included in the work of the thesis. Distribution of risk across system and technology uncertainty are another two drivers that are taken into account.

*Technology uncertainty* is decomposed into drivers that are directly considered and the ones that are related to the development process and observed indirectly. The process related factor includes *actors' familiarity with technology*. Since this driver is in direct relation with stability and assimilation of a personnel, the process-related factors from Chapter 2 include *skill, organization and communication*. Hence, when determining the technology level these process factors need to be taken into account. If the product is developed in coordination with a supplier, *vendor quality* is to be considered as well. The

product-related drivers that are directly considered in this chapter include *technology maturity, coupling and availability of substitute* that is represented as part of maturity in this work. Other factor that might impact technology uncertainty is ease of regulatory approval. It is considered that this process is external from a development process perspective. Hence, this driver is not considered. This is the reason why the influence arrow from approval to product performance is represented as dashed line.

Since the product is part of a development process, the cost and time can also represent drivers of the overall product performance. However, since the whole solution is developed for these factors (Chapter 2) they are not considered in this model. That's why the influence of cost and time in Figure 3.1 on product performance is presented as a dashed line.

This concludes the list of drivers that are to be considered for the creation of risk management solution for product under development. In order to finish with all the major assumptions that are driving the work presented in this chapter, in section 1.1.2, risk terminology is presented.

#### 1.1.2.Assumptions: Risk terminology

Having in mind that the goal of this section is to provide comprehensive risk management solution for product under development, risk terminology is based on the one used for development process risk (see Chapter 2, sections 1.1.1 and 1.1.2). As seen from the definition of performance risk, the focus is given particularly on uncertainty. Hence, the same (Thunnissen, 2003) classification of uncertainty is used: ambiguity, epistemic, aleatory and interaction. The same terminology is used due to the two main reasons. It is considered that Thunnissen's definitions are the most comprehensive. Thus, they are suitable for various problems in engineering fields, including this one. Secondly, the same terminology is a base for the merged process-product risk management solution.

The proposed solution is based on the aleatory and interaction uncertainty. Ambiguity is considered through the "requirements quality, simplicity and stability". However, it is to be represented in the aleatory manner. Here, it is necessary to emphasize that in this representation there is always a place for the "unknown unknown" epistemic uncertainty that is always present. Hence, it can be said that the goal is to reduce epistemic uncertainty by systematically dealing with the risk drivers.

Same as the development process, the product is observed as a system and in that sense it is decomposed into subelements (components, parts, etc). The drivers leading to change in performance of particular product element are to be present in the form of distributions. The performance risk of the complete product is obtained based on this individual component values and their interactions. In that sense, interactions need to be properly handled.

With all the previously mentioned in mind, two main issues are to be considered in order to provide adequate risk management solution for product under development. Firstly, what is the adequate decomposition of the product? Secondly, what are the relationships between the product elements that can represent the interaction and propagation of risk from one element to the other and from lower to higher levels? The second question is highly related to the first one. While decomposition of the development process came naturally, the same can't be said for the product. To name a few, the product can be decomposed based on its domains, parts, flows, features or requirements. Each manner of decomposition has its advantages and views that can be beneficial in performance representation. Hence, the goal of the state of the art presented in the section 1.2 is not only to investigate current risk approaches in product domain but to see the available decomposition and interaction models.

#### 1.2. Risk management for product under development - the state of the art

The state of the art has been conducted in two parts. Firstly, product-related, and risk-related domains are investigated. This includes safety, failure, maintenance, and other engineering domains that are highly influenced by risk. These domains are considered relevant for product representation, including elements that are used for decomposition and interactions between them. The identified solutions are presented in section 1.2.1. After, another domain is studied: change management. It is believed that solutions from this area can be relevant for risk propagation modelling. Hence, the identified solutions are presented in section 1.2.2.

#### 1.2.1. State of the art in the product-related domains

The main issue of this chapter is the adequate product decomposition and representation risk interactions between the product elements. The full list of analysed approaches can be found in Appendix A.2. Table 3.1 presents only the most influential ones from the perspective of the thesis.

System engineering ontologies have a good ability for knowledge management (L. Yang et al., 2019). Hence, it is no surprise that many approaches identified are based on system engineering. Schindel, (2010) has built a system engineering metamodel that integrates stakeholders, technical views, requirements, components, functional roles, interactions, states and inputs and outputs. In this and other system engineering approaches, the goal is to use MBSE as a mean to solve problems that appear in standard failure analysis like FMEA: arbitrary identification, sensitivity to analyst skill, no direct connections and others. Hence, MBSE engineering can be used as a base for failure analysis (Mauborgne et al., 2016). Or it can be combined with other methods like FTA (Rambikur et al., 2017). However, these models usually require quite detailed behavioural model. Oliva et al. (2010) propose comprehensive solution for failure management in maintenance context. However, this model requires detailed functioning information which is not always available during different product development phases.

The second group of articles is matrix-based. The matrix-based approaches are usually using some form of DSM that is modified according to their needs. Several papers make connections and define failure risk based on the functions, components and failure modes (Lough et al., 2008, 2009; Stone et al., 2005; Tumer & Stone, 2003). Da Cunha Barbosa & de Souza (2017) directly map different flows between the components and then calculate performance risk. Similar to these approaches is also matrix based approach proposed by Jiang et al. (2019) that represents the performance value based on principal solutions, subfunctions and correlations.

Complementary to these approaches are the network-based ones. Having in mind that DSM can be used to represent the network, they share the general idea of connectivity between elements. In the recent years, researchers are, thus, focusing on network characteristics and their properties to represent failure potential (Haley et al., 2016, 2014; Kasthurirathna et al., 2013). Different topological metrics are used to represent failure tolerance or behavioural degradation. Networks can also be used in combination with other approaches. Li et al. (2019) use Weighted LeaderRank algorithm and SIR simulation to represent module influence.

Authors	Product decompositionElement interactionsCalculates		Calculates	Risk method
(Tumer & Stone, 2003)	Functions and components	Failures	Failure modes	Matrix-based
(Stone et al., 2005)	Function (and flows) and components	Failures	Identify failures (modes)	Function-Failure Design Method
(Lough et al., 2008, 2009)	Function and components	Failures	Centre of risk	Matrix-based likelihood and consequence
(Schindel, 2010)	Component, Functional role, Feature	Functional interactions, states	FMEA generation	MBSE Probabilistia Palational
(Oliva et al., 2010)	Components, Flows (input and output attributes) and Functions	System functioning modelling based on activities (reliability)		Model: Bayesian network with object and relationships uncertainties, FMEA, FTA
(Goswami & Tiwari, 2014)	Product and Modules	Relationships between functional instances	Overall Enterprise Risk Index	Bayesian network
(Haley et al., 2014)	Functions and variables (behaviours)	Bipartite network	Failure analysis	Centrality and eigenvector centrality
(Bayar et al., 2016)	Manufacturing system elements, KPIs, parameters	Disruption, disruption features, propagation of disruptions	Expected performance	Immune system inspired Multi-agent
(Haley et al., 2016)	Functions and variables (behaviours)	Bipartite network	Behavioural degradation	Topological metrics
(Mauborgne et al., 2016)	System models	System models with hazards	Safety requirements	MBSE-based
(da Cunha Barbosa & de Souza, 2017)	Component and its severity	System component relationships (physical, energy, mass, information) and their occurrences and impact factors	Performance risk	DSM HAZOP Risk Priority Number
(Rambikur et al., 2017)	System models	Architecture	Failure analysis	FTA and System engineering (action diagrams)
(Jiang et al., 2019)	Subfunctions, Principal solutions	Correlation matrix of subfunctions	Performance value	Performance value matrix
(Y. Li et al., 2019)	Component	Function flows (energy, material, information)	Influential function module	Weighted LeaderRank algorithm Susceptible-infected- recovered (SIR) model

Table 3.1 Most influential product-related approaches

Similar to these approaches are the ones that are based on agent connections (Bayar et al., 2016) or Bayesian networks (Goswami & Tiwari, 2014). These approaches consider the connection that exists between the process result (product) and the process itself. This idea is shared in the thesis.

Lastly, several approaches may not be completely suitable for the current work of the thesis but globally underline some of the main ideas. Fernandes et al. (2014) and Amine et al. (2017) focus on imprecisions and incomplete design information. Hence, they clearly show the project or process related information on a product. Amine et al. (2017) use fuzzy approach to deal with incomplete design information, while Fernandes et al. (2014) show the manner to reconstruct historical data to represent time evolution of design variables. The later also connect the product domain with the change. Change is also underlined as crucial factor of product evolvability. Work of Luo (2015) deals with influence of product

architecture on evolvability of a product. Hence, even in the product-related domain change is recognized as important factor. Hence, the following section is dealing with change in general and in the context of its propagations.

#### 1.2.2. State of the art in change management

As seen in the previous subsection, product risks are usually observed purely in the context of failure. How one problem can lead to another and how all this will impact the functioning of the product, are the main questions that might appear in this area. The designers and engineers are usually the ones in charge to answer these questions. From the project perspective, product risks are seen as failure management and, hence, often considered as out of scope. And, this is where, in the context of development, one thing is almost always neglected.

"The design process is the course followed to reduce performance risk to acceptable levels", (Tyson R. Browning, 1999). The product passes through the series of issues and corresponding changes during its development. Each small problem and/or change in one component may lead to the problem in related component and that one can lead to another. These changes are causing "unplanned" problems since the project managers are more focusing on resources, time and cost risk management while forgetting that risk can propagate through the product and impact not only itself but the development process as well. Hence, we believe that the evolution and propagation of risks within the product is important for the development process as a whole.

Thus, apart from the "pure" risk management seen in the previous section, another area is covering problems that might appear during the product development. This is the area of engineering change management. Change management is dealing with the problems of rising changes during a product development cycle. From change requests and documentation, change propagation to change attitude, change management might be considered similar to risk management but the two are not usually directly connected. However, in this thesis, it is assumed that the approaches commonly seen in change management can be beneficial for the product risk management. Change propagation models can be adapted to deal with risk propagation.

Also, the solutions focusing purely on the product failures often don't give global view on product performance or quality. In that sense, it is hard to answer the following question: If the problem (risk) appears on one product element what will be its influence on the other product elements or the whole product? Since change management is observing the product in more general sense, their models might be more suitable to deal with the general product evolution through the development process. This section focuses on main aspect and definitions of change and the adequate literature from the area.

# 1.2.2.1. Change – general overview

The engineering change has two main domains: product and process (project). The product domain is by far more present than the process (Shapiro et al., 2015). Depending on the area, the change has several definitions. In the product domain, the most recent is the one that is the most appropriate in the context of the thesis:

"Engineering Changes are changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials etc.), behavior (stability, strength, corrosion etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behavior (design principles), or behavior and structure (physical laws) of a technical artefact", (Hamraz et al., 2013).

Similarly, process change can be defined as follows:

Design Process Changes "(*DPCs*) are changes and/or modifications, during process execution, to planned design activities (involved resources, tools, etc.), their resultant deliverables (drawings, documents, prototypes and generally descriptions of the technical artefact) or the relationships between design activities and deliverables (process structure)", (Shapiro et al., 2015).

Although it might be said that the second definition is more suitable for the process part of this thesis, it shouldn't be forgotten that in this chapter the process influence on the product should be considered. Hence, the change literature analysed in this section belongs to both product and project communities.

Globally speaking, the change can propagate in various ways: through interaction (behavioural, geometrical), medium and interface types (product variants, interconnected departments, suppliers), (Shankar et al., 2014). Studying them is important for the risk propagation, since the channels can be the same. Hence, the state of the art will cover the way the product/process is decomposed and how the links between the components have been established.

Methods considering engineering change can be divided into theoretical and a posteriori models. The first one are generally used to represent design alternatives and hence require tremendous amount of product knowledge. Hence, they are not in the scope of the thesis. The posteriori models, on the other hand, don't take into account exact equations but allows the representation of direction or nature of the changes. Having in mind their general scope, these are the model that will have a priority in the analysis.

1.2.2.2. Change management state of the art

Change management approaches of interest are shown in Table 3.2. The table captures propagation method and product/process decomposition depending on the focus of the identified solution. The full list of analysed papers can be found in Appendix A.3.

Authors	Focus	Decomposition	<b>Propagation method</b>
(Clarkson et al., 2004)	Product	Components	Change Prediction Methods (CPM)
(Hamraz et al., 2012)	Product	FBS linkage	FBS linkage and CPM
(Maier et al., 2014)	Project and Product	Components, iterations, changes, learning	CPM, MC and Discrete event simulation
(Wynn et al., 2014)	Project	Components, iterations, changes	Discrete event
(Ma, Jiang, & Liu, 2017)	Product	Design properties / parameters	Multi-variation (concurrent change) propagation based on multi-agent systems.

Table 3.2	Change 1	management	- the	e most	significant	articles

Change Prediction Method (CPM) (Clarkson et al., 2004) is one of the methods most widely used in this area. It considers product DSM and adds likelihood, impact and risk. It is used for direct and indirect propagation. However, it can't take into account concurrent changes. Several approaches that have adopted CPM suffer from the same problem.

The full list of identified approaches based on CPM can be found in Appendix A.3. Hence, only some of them will be represented here. Work of Morkos et al. (2012) is considered interesting since they directly address requirement change propagation. Requirements are important part of product risk, hence their propagation is of interest. However, the higher-order DSM approach that is applied here is subject to the same limitations as CPM.

Hamraz et al. (2012) have extend previous CPM work by introducing FBS linkage product decomposition that takes into account different product aspect that are subject to change (function, behaviour, structure). They define the links between these aspects as well. Having in mind that the focus of design is constantly moving between these three aspects, the decomposition of the product in this sense is considered the most adequate for the thesis. Hamraz et al. (2015) have also proposed a full FBS linkage ontology to address change propagation and its industrial evaluation (Hamraz & Clarkson, 2015). However, since the authors are using CPM, its limitations are still present.

In the project and project-product domain, two approaches are considered interesting. The priority policies considering engineering change are simulated using discrete event simulation by Maier et al. (2014). This approach holds the most similarities with the general thesis idea since it combines propagation through process and through product. However, the product is represented only through components and the impact and likelihood in this stage are not fully considered. Hence, distinct effect is not treated as intended in this chapter (however, that was not the goal of this article). Although Monte Carlo is used to enable concurrency, the propagation of change is limited since CPM is used for the maximal number of steps. While change propagation is considered limited, this is not the case with the risk. Hence, CPM is not considered as an adequate solution to determine propagation. Similarly to this approach, Wynn et al. (2014) have proposed purely project-oriented solution. They improve the previous problems by directly implementing likelihood and sensitivities to change. On the other hand, the change execution is performed downstream which is not always possible in risk management. Hence, these models can be used to support the general idea of the thesis and the modifications are needed to address the risk as intended in this chapter. More about the perspective of this and other solutions can be seen in the following subsection that is dealing with the synthesis of the state of the art.

Although purely product-oriented, in terms of a method, the approach proposed by Ma, Jiang, & Liu (2017) shows greater potential since the concurrent change propagation is naturally considered. They focused on likelihood and effect depending on different relationships between the parent and child nodes and upstream and downstream propagation. The solution is based on multi-agent systems. In their second work (Ma, Jiang, Liu, et al., 2017), the propagation likelihood is based on historical data. Although this work is not in the direct focus of the thesis it is worth mentioning since the solution is based on historical data. Hence, the importance of data in change management can be used to emphasize the importance of data in risk management. Also, these works show that new tendencies in change propagation are similar to the network studies in the failure community. In other words, the two communities can be merged to address the risk.

In terms of subject, several works are dealing with certain aspects that are of interest in this thesis. Ouertani (2008) proposed an interesting view on the project through dependencies between the product information. Siddharth & Sarkar (2017) don't include change propagation but they clearly emphasize the connection between design and manufacturing parameters. Similarly, Pasqual & de Weck (2012) have observed the propagation of effects between project and product though the engineer propagation DSM. Reddi & Moon (2012) observed engineering change management and new product development in the global manner. Hence, causal loop diagram and system dynamic method have been applied to consider project factors and their changes. In the terms of data it can be said that the engineering change domain may be better documented than the risk domain. For this reason, Do (2015) has proposed product data management database integrated with data mining module to predict engineering change. If risk domain becomes documented as this area, data mining techniques can be used to set the parameters of the model proposed in this thesis. Lastly, Eltaief et al. (2018) considered the change propagation from part CAD to the assembly CAD. Their change propagation solution is based on

correspondence associations between parts. It takes into account dimension modification, sketch modification, fillet, chamfer and draft modification and linear or circular repetitions parameter modifications. Hence, change can be considered in the practical (CAD) level, not only on the organizational one.

#### 1.3. Comparison and conclusion on the approaches identified in the literature

Based on the conducted state of the art, it can be said that risk and engineering change have a lot in common. Investigation in designed and manufactured product, showed that for over 50% of engineering companies consider change as a major source of their problems during development process (Jarratt et al., 2011). Similar has shown in our analysis of Kendrick's risk where "change" is listed as a separate risk category (see Appendix B). As a consequence, certain methods are applied in similar way in product-related risk management literature and in change management. With this in mind, the approaches from both domains are synthetized here from the aspect of their usability in the thesis.

The main criteria for desired product-related risk management solution are presented in Figure 3.2. Similarly as in Chapter 2, these criteria are based on scientific issues observed in this thesis. Hence, as indicated in the first scientific question, the core requirement is to find adequate product representation to enable risk behaviour representation. Risk behaviour includes interactions between needed risk drivers and the propagation of risk through the product. All the mentioned needs to be performed with risk management aspects in mind (question 5). In other words, the solution should be able to clearly cover risk identification, analysis and evaluation. Having in mind that the main goal is to provide a software solution, the focus is on evaluation phase. This phase needs to enable sufficient flexibility, including solution dynamic and tailoring (question 4). Hence, the approach should be capable to enable assessment of different scenarios through "what if " analysis.



Figure 3.2 Requirements for product risk management solution

After the requirements have been shown, the available solutions can be analysed from the aspect of their use in the context of the thesis. These observations are summarized in Table 3.3.

It may sound paradoxical, but the solutions seen in change management literature can be considered more appropriate than risk management solutions that are mainly focusing on failure. However, it shouldn't be forgotten that certain risk solutions are trying to take into account other factors than failure. For majority, on the other hand, this is not the case. This can be explained by the tremendous importance of failure detection and prediction. However this should not justify the one-sided view on risk since the neglected risks in one domain can show their face in the other. This is why it is believed that the combination of views presented in these two communities can provide a comprehensive risk management solution for product under development.

	Pro	oduct d	ecompos	sition		Inter	actions	3		Problem propagation						
Method → Criterion↓	Component	Function, failure, component	Function, Behaviour, Structure	Design parameter	Matrix	Network	Bayesian network	Markov model	Agent communication	Discrete event simulation	System dynamic	Agent-based simulation	Change Prediction Method + Monte Carlo	Network parameters	Markov model	Bayesian network
General enough to be applicable for all development phases	+	++	+++	+++												
Capable to represent product components					+++	+++	+	+	+							
Ease in representing effects, probabilities, and sensitivities					+++	+++	++	++	+							
Ease of representing multiple factors					++	+++	++	++								
Concurrent appearance										++	+++	+++	++		+	+
Dynamic behaviour										++	++	+++				
Propagation path representation										+	+++	+++	++		+	+

Table 3.3 Synthesis on the identified approaches

The solution identified in the change literature is the one most suitable for product decomposition. Based on the design theory, FBS linkage shows the greatest potential for product decomposition since it covers all the aspects of a product. Using this approach, the product can be represented through different sets of design parameters. For this reason, the approaches based on general design parameters can also be used in the thesis context (see Table 3.3 – product decomposition).

Networks are identified as important base for both failure and change propagation. At the same time, they show the greatest potential to represent the connections between different product aspect and their parameters. Their biggest strength is their modularity. Matrix approach would require a new matrix for every connection defined, while with the networks nodes or layers can be added with more ease. Also, network in combination with other approach can support numerous different views: different parameter can be represented or different connections. Bayesian and Markov model are more probability oriented. Hence, they may require information that is not easy to furnish. Networks on the other hand support analysis based only on their topology and the one with the additional information.

In terms of propagation, the chosen approach is the agent-based simulation. This approach can be seen in both product and change literature. It enables implementation of different factors through behavioural modelling. Concurrent and random events are enabled using the connections between agents. Propagation path is not known in advance and can be one of the results of the model. In other words, the biggest strength of this approach is that it can identify unpredictable paths (the ones not imagined by the user). Having in mind that the risk events and their propagation are unknown, agent-based solution with SIR simulation is considered as the most adequate. It is considered that SIR can provide the needed randomness to the model.

After identifying the approaches considered adequate for the thesis, another aspect needs to be analysed. In change management, any change positive or negative is modelled through the same propagation. The events may be concurrent or event conflicting, but the model is still based on the one "flow" – the change propagation. In risk management problems and their solutions are propagating at the same time caused by different sources. Hence, two different "flows" are necessary. Hence, contrary to the identified change approaches, the thesis needs to consider problem propagation and solution propagation separately. This is one more reason why naturally dynamic agent-based models are suitable for the modelling of thesis problem.

Lastly, it needs to be emphasized that this comprehensive approach haven't been identified in the literature. Hence, the work presented here can be considered as step forward in risk (and change) management approaches.

# 2. Risk management for product under development – the proposed framework and the model

More than in the process domain, product risks are often counted solely on the failure level. However, this is just one part of the product risks. As it has been shown in subsection 1.1.1, product performance risk depends on, both, process-related and product-related factors. Also, product can be a medium through which risk propagates from one part to the other. Hence, instead of being surprised when the conditions in product development change, it can be decided to go and examine the possible reasons for those unexpected problems. This is the goal of this chapter – get to know the product and their risk and make a solid foundation for process-product integration (presented in Chapter 4).

Once again, the goal is to get to know ourselves to fight the unexpected. The conduced literature analysis in product domain has shown that it is either the unknown (epistemic risk events) that is in focus or the specific behaviour (failure behaviour). Although it might be said that certain (partially) adequate solutions exist (like the ones of change management), that are not used in the risk manner. Anyway, the solution proposed in this chapter is aiming to overcome these issues. Hence, in Section 2.1 firstly the main idea of the risk management solution for product under development is presented. The framework is presented in Section 2.2 and the model in Section 2.3.

#### 2.1. Risk management for product development - the main idea

The main idea is organized around product performance. Product performance is an important parameter of a development process. While it is obviously the main product parameter, it is often one of the indicators of the whole development process. Hence, product performance is often used as a criterion for design tasks. The satisfactory performance would imply the continuation of the development process, while the unsatisfactory level would require investigating and improving the current activity and the product. In any case, the importance of product performance is evident.

As explained earlier, in this thesis product performance is considered globally (see section 1.1.1). It represents uncertainty that the desired performance will be achieved. Consequently, it depends on different factors and product elements forming the final product or a system. The main idea, thus, can be presented in Figure 3.3.



Figure 3.3 Risk management for product under development : the main idea

Different causes (see 1 in Figure 3.3) can lead to the changes related to individual product element (see 2 in Figure 3.3). These changes can be negative or positive. Negative implies problem generation on the individual problem element, while positive represent solutions to the problem. Hence, two main influences can be observed in the individual product element: problem and its solution. Here, the product element represents adequate element based on which product is decomposed into units of smaller granularity. Product elements are connected to each other based on the dependencies of different kind: information, physical laws, designer relations or any other. Since causes lead to the change in values of different parameters of product element, these new values may lead to the problems in other product element based on the established connections between elements. The propagation of problems is not deterministic, but rather random and dependent on the connections, probabilities and sensitivity between elements. The connections and the propagation can be seen in 3 in Figure 3.3. Hence, performance of the individual element depends not only on the causes that directly affect it, but also on the other elements with whom it is in direct or indirect contact. Hence, the risk propagates from one

element to another and forms product performance risk (see 4 in Figure 3.3). In this work product performance risk is observed through the current values of individual performances.

The main idea can be illustrated through one simple question: How product performance will change if the design activity is not well performed? Having in mind that each design activity defines at least one design parameter, it can firstly be said that design activity is setting the parameter value for one product element. If another element is based on information of that product element, there will be a connection between them. Hence, the parameter value defined through the activity may impact the other product elements and their values. In that sense, if the quality of the performed activity is uncertain, this uncertainty will be partially or fully illustrated in the individual product element performance risk (uncertainty). Also, it will propagate to other elements and impact different product elements performance risks. Hence, the performance uncertainty of the whole product will be affected.

Detailed information on the proposed framework and the corresponding model are represented in the following subsections.

#### 2.2. Risk management for product development – the framework

Framework for risk management solution for product development is based around the general idea, knowledge on process solution presented in Chapter 2 and with the guidance of performance risk definition by Browning (1998), presented in section 1.1.1.

Contrary to the process risk management, the goal of the product solution is not to consider all the individual risk events and their influence on performance. The identification of influential factors is based on Browning's framework and it includes influence of design tasks, requirements, and technology. The thesis, hence, has a goal to move this study to more practical domain and to enable quantitative analysis and evaluation of performance risk. Going back to the main idea, it is necessary to emphasize that the risk causes are no longer general. As it can be seen in Figure 3.4, they are limited to design task, requirements, and technology.



Figure 3.4 Risk management for product under development: framework based on the main idea

These three factors can be assigned to every product element. However, they propagate individually. Technology issue in one product element can cause technology issue in the other. Currently, it is not considered that technology issue can provoke problems in requirements or with the design task quality. If this aspect is to be represented, product element behaviour would have to be defined in the similar way as it has been done in case of task behaviour in Chapter 2. This is considered out of scope for this solution. On the other hand, it shouldn't be forgotten that the goal of this solution is to be integrated with the process one. In case of integration, previously observed technology problem can influence design task quality. If the technology information is listed as one of the input or control information for

the activity (as it should be), any change could lead to the change in the design task value using the behavioural model presented in Chapter 2.

In this model, as it has been said, different factors propagate separately since they are considered as different problems. However, they form the product element performance risk and consequently product performance risk together. Change in the value of either design task quality, requirement or technology would lead to the change of performance risk.

In order to better illustrate framework proposed here, concepts used can be directly related to the product performance drivers (presented in Figure 3.1). Figure 3.5 shows product performance drivers and concepts used in this thesis.



Figure 3.5 Risk management solution for product under development: conceptual framework

The framework includes drivers and their relationships to the performance risk that are considered in this thesis. It has already been stated in section 1.1.1. that the main drivers can be divided into process and product related. Process factors are represented in dashed lines (and in orange) in Figure 3.5 and they are considered indirectly. They are the subject of Chapter 2, hence the results from this model can be used as inputs to the product model. It is assumed also that the inputs in the product model can also be provided by the user even without the use of process model. Hence, the solution can be applied independently or depending on the process model.

Starting from the process factors, the framework firstly considers influence of the development task. Since each task is related to at least one product element, it can be said that the quality of the development task influences product element performance. This influence is represented in form of the variable marked as "V" in Figure 3.5. Letter "V" has been chosen to represent this parameter since it is

the activity value risk from the process model that is used here. In case the process model is not used, user can judge the performance quality for each activity designing a product and relate it to appropriate product element.

Other process parameters are used to represent familiarity of the actors with the technology applied in the product development. Hence, as it can be seen in "T" in Figure 3.4, technology variable depends on skill, communication, organization and vendor quality parameters from process model. In case the process model is not used, when assigning initial value to technology variable, user needs to take into account the knowledge related to the applied technology. The other factor that influence the technology parameter is the maturity of the technology. This driver is product related and it shows the general advances in the area and novelty of the product and/or processes used. If the technology is less mature and/or knowledge about it is scarce, the value of "T" variable will be lower and it will indicate bigger potential issues.

The other factor that influences product performance risk is related to product requirement. Shown in "R" in Figure 3.4, requirement variable represents quality, simplicity and stability of the requirements imposed to the product. Each requirement is related to adequate product elements and its value drops as quality, simplicity and/or stability decreases. Initially it can be assigned by the user. Same as technology and value, it evolves during simulation.

Other drivers impacting the product performance risk includes product complexity, distribution of risk and coupling. They are taken into account based on the developed model. Hence, letter "M" is used to depict them in Figure 3.5. The model is based on FBS linkage product decomposition, agent networking and simulation. It enables propagation of influences from one product element to the others. The detailed information about it is presented in the following subsection.

It is necessary to emphasize that this model structure is not only used for problem propagation. Since every risk problem requires the solution, once this solution is found it is necessary to propagate it to all the potentially affected product elements. This is why in the thesis propagation includes two flow types: propagation of problems and propagation of their solutions.

Lastly, design iterations are also considered. Value, technology and requirement variables evolve based on their current values and influences from connected product elements. Hence, their values are used as a condition for the new iteration. If value, technology and/or requirement parameter value is lower than desired, new iteration is necessary to provide solution to the encountered problems. Each iteration has predefined iteration productivity that improves the solution by a specified percentage (marked as "I" in Figure 3.5). This parameter is known in advance and can be the same for the whole product or specific to each product element. Consequently, the number of iterations necessary to reach desired variables values is not known in advance and it depends on the iteration productivity parameter and on product dynamics.

Having in mind the main idea and the framework proposed to represent risk propagation for product performance, the model is described in more detail in Section 2.3.

# 2.3. Risk management for product development – the model

In this section model for the product performance risk is presented. The model is formed around agentbased methodology. Having in mind that several parameters have been introduced in the framework, here, the distinction between them and agents is clearly identified. The section includes general model presentation in section 2.3.1, followed by the product decomposition explications in section 2.3.2. Section 2.3.3 explains the risk propagation principle used in the model. Performance and severity evaluation are shown in Section 2.3.4. Lastly, model randomness is covered in Section 2.3.5.

# 2.3.1. General model



General risk model for product performance risk prediction is presented in Figure 3.6.

Figure 3.6 Risk management for product under development: general model

The central element of the model is product element, presented in 1 in Figure 3.6. It is modelled as an agent. Product element is based on FBS linkage ontology (Hamraz et al., 2012, 2015) and it can be structural, behavioural of functional element of any detail necessary. More generally, it can be defined as design parameter in the broader sense of its meaning. Detailed information about product elements are presented under product decomposition in section 2.3.2.

Product elements has risk factors (see 2 in Figure 3.6) that form product element performance risk (see 3 in Figure 3.6). Risk factors are variables of product element agent. They are initially defined but they also evolve during the model run. Risk factors are defined based on the proposed framework and include technology, requirement and value parameters (marked in 4, 5 and 6 in Figure 3.6, respectively).

The current value of all the variables, but also the product performance is represented using severity. The severity can be unsatisfactory or satisfactory. Satisfactory severity (see 8 in Figure 3.6) implies that no problem is encountered and consequently no additional tasks on the activity level are necessary. Unsatisfactory severity (see 9 in Figure 3.6) indicates problem and consequently requires a solution (see 10 in Figure 3.6). The solution directly changes severity value of one or more risk factors and product element performance risk. This change depends on the iteration performance (see 11 in Figure 3.6) that is defined either for each activity or on the product level. For example, it can be stated that each additional iteration improves the solution by 20%. In that case, iteration performance is set to 20% for all solution activities.

Solution to the problem is just one way to change severities. The other one is based on the propagation of problems or solutions from other product elements. In order to enable this propagation, each product element can have one or more connections (see 12 in Figure 3.6). The connection between the two elements is described using likelihood and sensitivity. Sensitivity (see 13 in Figure 3.6) describes how

sensitive one element is on the changes in the connected element (parent element). Here, changes include both problems and solutions. Likelihood (see 14 in Figure 3.6) on the other hand, defines the probability that the problem or solution will propagate to the particular product element.

Hence, how influential one product element is, depends on several factors. Firstly, it depends on its severity. The severity is the initiator of the change in other product element(s). Secondly it depends on the sensitivity between the two elements. Large perturbation in parent element can cause a small change in the connected element if the sensitivity is low. Finally, it depends on likelihood. Likelihood defines the probability that the problems or solutions in the parent parameter will propagate to the particular child parameter.

Since the product or system (see 15 in Figure 3.6) is composed of product elements, problems and solutions appearing on this level directly form product or system performance risk (see 16 in Figure 3.6).

The next subsection details product decomposition representing the base for risk drivers and their propagation.

#### 2.3.2. Product decomposition

The product is decomposed into elements of interest based on FBS linkage model (Hamraz et al., 2012, 2015). Hence, in this section the main definitions related to the model will be presented to enable clear understanding of the proposed model.

Based on Gero's (1990) FBS framework, FBS linkage has two main assumptions. Firstly, it is assumed that the product can be decomposed into different abstraction levels that includes systems, subsystems, components and parts. Secondly, on any component level structures and behaviours can be described. Functions are described at least at the product level. Hence, product is decomposed into functional, behavioural and structural elements and the links between them. The illustration of FBS linkage of a product is shown in Figure 3.7.



Figure 3.7 FBS linkage model of a product

"F to F" layer represents product functional elements and their links. The functions describe the purpose of the product. Based on FBS linkage ontology, functions can be decomposed into functional elements to the level where they can be linked to behaviours. The links between functional elements are enabled

based on material, energy and information. If the simple product like hair dryer is considered, functions can be "generate air flow", "generate heat" and "mix air flow/heat and focus hot air flow". It is clear that those functional elements are connected with air and thermal energy flows.

"B to B" layer represents behavioural elements and their links. Behaviour describes what product does and it is made of behavioural attributes. Behavioural attributes represent the group of physical properties. Behavioural links are established between the behavioural attributes that contribute to the same physical law. For example, in the case of a hair dryer it can be said that the fan and casing thermal elements are connected.

"S to S" layer represent what the product consists of. Structural elements are attributes describing the design. They might be grouped into geometry, material, surface, colour and controller. The links are established between the structural elements of the same attribute. Hence, casing geometry of a hair dryer depends on the fan geometry, among others geometries.

FBS linkage defines the connection between these three layers. All the relations are many-to-many, but certain differences between them can be distinguished. Function-behaviour links ("B to F" and"F to B" in Figure 3.7) are used to describe measurable effect of an object. They are considered rational and subjective links depending on designer's goals, experience and knowledge. In hair dryer, function "generate heat" depends on the thermal behaviour (heat) of the heating unit.

Behavioural attributes are realised by structural attributes. This connection is shown through behaviourstructure links ("S to B" and "B to S" in Figure 3.7). They are causal and objective. Thermal behaviour of the heating unit depends on the heating unit material.

Further details on FBS linkage ontology can be found in Hamraz et al. (2012, 2015) and the corresponding literature based on which the ontology is developed.

The usage of FBS linkage in the thesis differs from its original use. Here, each FBS element is represented as an agent and described with three variables (value, technology, requirements). Hence, the elements have severity value(s) that can be assigned to them. The links between the elements are accompanied with the sensitivity apart from the original likelihood (and impact).

After decomposition has been detailed, next subsection shows how risk propagates through the product.

# 2.3.3.Risk propagation principle

Risk propagation is based on modified SIR simulation. SIR stands for "Susceptible", "Infected" and "Recovered". The SIR problem is one of the common epidemiological problems. The model is used to describe movements in the population between different states of the model (susceptible, infected, recovered). It is described with infection rate and recovery rate. Originally, the problem is represented in the form of ordinary differential equations, but recently many authors are using agent-based simulation to represent and solve the problem.

The SIR model is sometimes used to represent problems out of the epidemiological field (Y. Li et al., 2019). In the thesis, it is assumed that the product problems and their solutions are propagating through the product in the same manner as the virus through the population. Hence, in the same way as the virus is spreading through human contact, the product problems are spreading based on the connections between product elements. The probability of spreading is defined through the connection likelihood.

To fully suit thesis needs, SIR model has been adapted to consider solution propagation and effect calculation. Instead of three states, like in original model, one more state has been added to the system. Product element can currently be susceptible (to problem), problems spreading, solution spreading and finished. Initially, all product elements are susceptible. The product element moves to "problem

spreading" once the problem is encountered. Once the solution to the problems is found, the product element moves to the "solution spreading" state. Finally, when all conditions regarding the solution are met, the product element moves to the "finished" state.

Transition from "susceptible" to "problem spreading" state in a decomposed product is presented in Figure 3.8. The product element and the connections in grey represent "susceptible" state. Black nodes and links are showing the "problem spreading" state. It is assumed that the initial problem has appear on the structure ("S to S") level. From that node the problem has spread to two nodes in behavioural layer. Finally, the functional element has been affected by a problem. The link based on which the problem has been spread are shown in black. It can be remarked that in the next model step, the problem can spread to one of two possible nodes in structure layer, one node in behavioural layer and one node in functional layer.



Figure 3.8 Principle of problem spreading in a decomposed product

Product elements move from one state to the other based on the random events and likelihood of connections. In each state, the calculation of severity is performed. Detailed information on severity calculation is shown in subsection 2.3.4. Explanation considering model randomness are presented in subsection 2.3.5.

#### 2.3.4. Risk factors, performance and severity calculation

As mentioned earlier, product element is described with three variables: value, technology and requirement uncertainty. Value risk factor represents the influence of the design task on the product element. This variable implies that if problem appears on the development level, its influence can be directly linked to the product element. Technology uncertainty includes uncertainty related to technology drivers. This unique technology value for each structural, behavioural and functional element enables simulation and comparison of different solutions. Requirement uncertainty represents all problems related to the definition of desired product characteristics and their stability. The values of all these variables belong to [0, 1], where 1 indicates no risk and 0 highest risk. They are initialized at the beginning of the simulation.

The risk factors (value, technology and requirement) form performance risk of a product element. Hence, this calculation needs to be defined. The calculation is inspired by the work developed by Benaben et al. (2019) who have used force polygon to represent the influence of different risk events. In the thesis it is assumed that the technology and requirement bound the performance level. In other words, product or its element can be as good as the available technology (T) and its requirement (R). The value (V) act as a multiplier to this bounded performance. If the design activity is performed without any error, the product element performance is limited by technology and requirement only. If the error is accounted, the performance will diminish accordingly. The problem is illustrated in Figure 3.9.



Figure 3.9 Product element performance calculation

Imagine that the initial uncertainties are set as follows: T = 0.7, R = 0.6 and V = 0.95. The risk factor impact can then be defined as risk value deducted from 1 (see r and t calculation in Figure 3.9). The joint problem impact of technology and requirement is determined as a resultant of the two (see rt calculation in Figure 3.8). It is assumed that the two vectors representing technology and requirements are perpendicular. Once the merged problem is determined, its influence is translated in the form of risk (RT in Figure 3.9). Finally, performance (P in Figure 3.9) is calculated as a product of value risk and RT risk.

Once all the factors and performance are defined, it shouldn't be forgotten that during the simulation run, their severities evolve. Severities values are calculated differently for problem and solution propagation.

For problem propagation, severities depend on its current value, value of the element impacting the change in severity and sensitivity between the two elements. Sensitivity ranges between [0, 1] with the step of 0.1. Zero severity indicates that there is no link between the two elements. The severity calculation for the linked elements is based on (Ma, Jiang, & Liu, 2017; F. Yang & Duan, 2012) and formulated as in the Figure 3.10.



Figure 3.10 Calculation of technology severity for a product element

As seen in the figure, the technology problem on the first node causes technology severity change in the second node. Having in mind that the technology uncertainty  $(T_1)$  of the first node (and its corresponding impact  $t_1$ ), sensitivity  $s_{12}$  and the current value of the child node  $(T_2^{current})$  are known, the new value of technical severity  $(T_2^{new})$  is calculated as follows:

$$T_2^{new} = T_2^{current} - \Delta T_2 = T_2^{current} - s_{12} \cdot t_1 \cdot T_2^{current} = T_2^{current} \cdot (1 - s_{12} \cdot t_1)$$
(3.1)

$$T_2^{new} = 0.8 \cdot (1 - 0.1 \cdot 0.3) = 0.776$$

Equation 3.1 can be applied on all risk factors (RF):

$$RF_j^{new} = RF_j^{current} \cdot (1 - s_{ij} \cdot rf_i)$$
(3.2)

Where node i influences node j.

As it can be seen, the calculation of risk factor severity when sensitivity is equal to 1 correspond to the reliability calculation in a serial system. This is in accordance with the literature that doesn't consider sensitivity between the connected risks.

In the case of solution propagation, the solved parent node can initiate solving of the child node. In this case, the current severity is improved based on the iteration productivity:

$$RF^{new} = RF^{current} \cdot (1+I) \tag{3.3}$$

Where I is the iteration productivity.

After the calculation, the model randomness impacting the values needs to be detailed. This is performed in the following subsection.

#### 2.3.5.Model randomness

Model includes two types of randomness: random problem and first solution appearance and random propagation of risk.

The first one is used to initiate the simulation. In this case, two options are supported by the model: random choice of one or several product elements and their risk factors on which the problem has appear or the activation by the user. In the first case, based on the problem appearance rate, problems are randomly generated on the product element. In the second case, user activates the node and risk factors of interest. The second option is used for "what if" analysis. The solution can appear in the similar way. However, in the case of the solution appearance delay needs to be defined. Delay represents the time between the generation of the first problem and the appearance of the first solution. In this way detectability of the problem and its influence can be studied.

In the case of random propagation of risk from one element to the other, it is the likelihood of the propagation that determines the path. The likelihood is a characteristic of a connection between the two nodes that depends on the strength of the link. Having in mind the strengths of all output links from the observed node, likelihood of propagation can be calculated and assigned to each link. The propagation during the simulation is then determined randomly, based on the obtained probabilities. For example, in Figure 3.11 all connections have strength equal to 1. Hence, there is p(0.25) that the problem will propagate to one particular node.



Figure 3.11 Link strengths

Lastly, having in mind that the model is based on random events, one simulation run represent only one possibility of product performance propagation. For this reason, Monte Carlo simulation is supported

by the current model. Performing predefined number of runs and developing proper statistic enable to have a more general view of the product performance risk.

#### 2.4. Conclusions on the proposed framework and the model

The framework and the model proposed in this chapter deal with the comprehensive definition of the performance risk. They enable inclusion of drivers that originate from both product and the development process. The proposed solution uses modified epidemiological model (SIR model) to capture propagation of problems and their solutions through the product development.

The decomposition of the model enables its use in different phases of development. The propagation can be limited to the known product elements (functions only or both functions and behaviours) in the first conceptual steps.

Solution enables propagation of problems and its solutions. This approach is not identified in the current literature and enables direct connection with the process risk management. This connection will be further elaborated and developed in Chapter 4.

The model enables studying of different dependencies between the product elements. From their sensitivity to the likelihood of propagation, different scenarios can be investigated. Single simulation enables representation of one possible propagation path and its performance risks. Monte Carlo simulation enable further investigation into general performance behaviour.

Although currently the framework requires certain information, it is assumed that this and other similar work will call for systematic data collection which is not as common as it should be in the risk management domain. The proposed model is thus ready to use information from digital sources as well.

# 3. Risk management for product under development – the software solution

The proposed model represents the base for the developed software solution. This solution is to be used for evaluation and prediction of product performance. The general description and detailed organization are presented in this section.

#### 3.1. General software organization

General software organization is quite simple. It is presented in Figure 3.12.



Figure 3.12 Product risk management software - general organization

As it has been shown in the model, the solution is fully based on agent methodology. Hence, the whole modeling is performed in agent-based software AnyLogic. The information necessary for model

functioning are defined in the Excel table that is imported into AnyLogic database. Database is updated before each simulation run.

Contary to the process solution, no software furnishes necessary data to the database. This is considered out of scope for two reasons. Firstly, certain information (like activity value) can be gathered from the proposed process risk management solution. This connection will be detailed in Chapter 4. Secondly, the information needed for simulation are closely related to design and designers. Hence, it is left to them to chose the appropriate way to determine the data. It can be based on the experience or determined manually or using one or more design tools and methods. Anyhow, the table information is predefined. Since, the standard tool is used (Excel), if need be, it can be easily connected to enable population of data. However, this problem is considered case and user specific. Hence, the input to the database is left undefined in Figure 3.12 (see the left arrow).

#### 3.2. Software structure

The software structure is based on the behaviour of the agents composing the model. The model includes three agent types corresponding to FBS linkage. Structure, behaviour and function agents are created. Each agent represents the corresponding product element. One agent type can have as many individual agent as needed to decompose the product. Agent networks are formed to represent functional, behavioural, structural, functional-behavioural and behavioural-structural links. The links are characterized with only two parameters: strength (likelihood) and sensitivity. The agents require detailed information regarding its parameters, variables, functions and states to enable proper software functioning. They are, therefore, presented in the rest of this section.

All agent types share the same structure and it is just the data that distinguish them. Having in mind that the solutions applies modified SIR simulation, agents' states are defined accordingly. As represented in the statechart in Figure 3.13 each agent can be in one of the following states at the time: susceptible, problem spreading, solution spreading and finished.



Figure 3.13 Agent's states

In order to enable proper flow between the states different elements have been defined. Table 3.4 lists those elements. Table 3.5 connect agent states, their activation mode and the executed functions.

Due to the constant communication between themselves, agents hold the information about their unique identifier. The networks are described in form of the collections to capture their strength (likelihood) and sensitivity. Hence, for every connected agent the information about its ID and link towards him is stored. All the network characteristics (likelihood and sensitivity) are represented as a float value between [0, 1]. These data are used for random problem and solution propagation.

As stated before, risk factors are captured in the form of variables: ValueSeverity, RequirementsSeverity, TechnologySeverity and PerformanceSeverity. The variables hold a value that belongs to [0, 1]. They are initialized at the beginning of the simulation and they evolve during its runs.

Agents	Parameters	Collections	Variables	Functions
Structure		Behaviours and structures connected to the observed structure and their corresponding strengths and sensitivities. Collection for distribution based on the strength of all connected elements (behaviours and structures)	ValueSeverity RequirementsSeverity TechnologySeverity PerformanceSeverity	problemSpreading() solved()
Behavior	ID	Behaviours, functions and structures connected to the observed behavior and their corresponding strengths and sensitivities. Collection for distribution based on the strength of all connected elements (behaviours, functions and structures)	ValueSeverity RequirementsSeverity TechnologySeverity PerformanceSeverity	problemSpreading() solved()
Function		Behaviours and functions connected to the observed structure and their corresponding strengths and sensitivities. Collection for distribution based on the strength of all connected elements (behaviours and functions)	ValueSeverity RequirementsSeverity TechnologySeverity PerformanceSeverity	problemSpreading() solved()

#### Table 3.4 Agent types and their design elements

#### Table 3.5 Agent states and their characteristics

States	Activation	Functions
Susceptible	Initially active	
Problem spreading	Activated by receiving message from another infected agent or by the user	problemSpreading()
Solution spreading	Activated by message from another resolved agent or by the user	solved()
Finished	Activated by messaging itself if condition is met	solved()

Lastly, two functions are needed to enable model working. One is used to spread the problem and the second one is used to spread the solution. As it can be seen in Table 3.5, problem spreading function is used in the problem spreading state. The solution is spreading in solution spreading and finished state.

Knowing the elements of the solution is just one part of a picture. The question is, then, how does it all work? Agent functioning is described using the algorithm presented in Figure 3.14.

Initially, agent is in the susceptible state. It stays in that state until the problem has been encountered. The agent identifies the problem by receiving the problem message. This message is delivered to the agent either randomly at the beginning of the simulation or from the agent that is in problem spreading state and, hence, spreads the problem. At this time, it is necessary to emphasize one detail regarding message sending. Since this process is performed randomly, it may happen that the agent receiving the message is already in the destination state. In that case, its state and severities will not be affected.

Once the problem message is received, the agent moves to the problem spreading state. In that state, firstly, new severities are calculated based on the equation 3.2. Secondly, as long as an agent is in this state, it can send problem messages to other agents.

Agent stays in the problem spreading state until solution is found. The first solution in the simulation is delivered randomly or by user preference to one of the agents after predefined time upon problem identification. Hence, the solution message can be delivered to the agent either as the first solution or through the message from other agents that are in solution or finished states.

Once the solution is found, the agent moves to solution spreading state. Here, new severities are calculated using the equation 3.3. After that agent starts spreading the solution by sending messages to random agents. If the performance and/or risk factor values are satisfactory the agent messages itself and moves to finished state. If the values are not satisfactory, agent performs one more iteration and

calculates new severities based on the equation 3.3. If in the meantime agent receives problem message it goes back to problems spreading state, repeating all the steps of this state.

If agent moves to finished state, it continues to send the messages about problem resolution. It stays in this state until either new problem appears (which takes it to the problem spreading state again) or until last element is finished which terminates the simulation.



Figure 3.14 Behavioural algorithm of one agent



Figure 3.15 Model dynamic

The model dynamic is shown in Figure 3.15. At the beginning of the simulation, all agents are in susceptible state (indicated in 1 in Figure 3.15). After the problem appears on the first agent, it starts sending messages to random connected agents (see 2 in Figure 3.15). The agents continue to spread the problem, which may propagate to all product levels (see 3 in Figure 3.15). After a time delay, the first problem is solved (see 4 in Figure 3.15). From this time on, problems and solutions are spreading together. This implies that the element can go several times through problem-solution states before moving to other states (see 5 and 6 in Figure 3.15). If the conditions are met, the solved agent can go to finished state (see 6 in Figure 3.15). However, even from this state agent can go back to problems spreading state. The goal of the model is to solve all the problems (see 7 in Figure 3.15) and to have all the agents in the finished state (see 8 in Figure 3.15).

#### 3.3. Conclusion on software development

In this section, a simulator for product risk management has been developed. The solution is based on agent technology and, as it has been shown through its dynamics, it is capable to capture risk propagation that may appear in the development. Two flows (problem and solution) and concurrent events between them and internally, are reflecting the situations that can be seen in product development. The errors made on one product component, propagate further in the product if the error is not detected. And once it is detected, the correction is not usually performed uniformly and at the same time on all affected components. These types of problems are well described in the proposed solution through the calculation of product performance based on the current situation of the product.

The structure based on agents, their networks and modified principles of SIR simulation is the heart of the solution. It enables to represent individual scenarios or to provide general information on product behaviour through Monte Carlo simulation. In Figure 3.16, a glimpse of its creation is shown, while in the next section the focus is given to the user perspective.



Figure 3.16 Development of the simulator for product risk management

After software development has been shown, the next section focuses on the user perspective and solution utilization.

#### 4. Risk management for product under development - solution utilization

The ultimate goal of any solution is to be used. Hence, the solution utilization perspective is proposed in this section. Having in mind that the goal of the thesis is to cover risk assessment procedure, the section starts with the view of the solution from the perspective of risk assessment. After that, the impact of the solution on decision-making is presented.

#### 4.1. Risk assessment and the simulator

As stated previously, risk assessment procedure includes identification, analysis and evaluation of risk. Mapping of the solution on these steps is presented in Figure 3.17.



Figure 3.17 Risk assessment and the proposed solution

Having in mind that the solution is based on the Browning's (1998) framework of performance risk, it is considered that the main part of risk identification has already been performed. The main risk sources include technology, requirements, design process and the product and risk configuration and they are all included in the proposed solution. Hence, from the user perspective risk identification is not performed. However, if the risk database exists, it can be used to create the network of events around each of these drivers. This may add in the second step – where the severities, strengths (likelihood) and sensitivities need to be assigned. In case this information is not available, the mentioned steps can be performed without it.

Risk assessment is covered using the developed solution and it is performed manually. It is strongly based on the product decomposition, FBS linkage. The product in the thesis is made of product elements (functional, behavioural and structural) and the connections between them. With this in mind, the user needs to assign all the risk severities associated to product elements and to describe connections between them using strengths and sensitivities. Hence, the risk analysis in this work is performed in two ways: explicitly and implicitly.

Explicit part of analysis includes definition of risk factor severities. In this step the user needs to judge the current level of technology, resource and process uncertainty associated to every product element. The solution support quasi-qualitative definition of these values. What differs in this risk approach

comparing to the ones commonly used, is that the user is asked to judge uncertainties in the factors that directly concerns him or her. Designer performing a design is usually aware if the requirements are not clear, technology is not stable, or design process is not working as it should. Hence, rather than asking in cost and time metrics, this approach is demanding the information about something that is already in the centre of user's attention.

Implicit part of assessment differs from common risk procedures even more. In this step the user is not asked to judge any of the risks. It is demanded to provide information related to general connections between the product elements: how sensitive two elements are on one another and how strong is their connection. Again, it is the information that designer is using daily.

Risk analysis can, hence, be supported with the methods or solutions that designers are already using to analyse their product. In that sense, rather than being a separate process, it becomes part of the design.

After analysis, risk evaluation is performed. Having in mind product decomposition, it uses severities, sensitivities and likelihood obtained in the previous step and problem and solution triggers as an input. This step is performed in the proposed simulator. It can include single propagation or Monte Carlo analysis for global performance behaviour. Its influence on decision-making is shown in the following section.

#### 4.2. Implications on decision-making

Proposed solution is intended to be used as the input into decision-making. It provides information about the performance risk for every product element. Hence, the obtained information can be used in several ways.

Firstly, propagation paths can be studied in two ways: individually or globally. Individual studies include either "what if" analysis of a particular event or a random event. Hence, they can be used for identification of risks on systems level. Global path analysis includes Monte Carlo simulation and provides information on general product performance behaviour. In this way, critical components can be identified.

Secondly, the solution can be used to study the influence of different modules or technologies. This process can be based on "what if " or general analysis. The results from different solutions can be easily obtained since only the desired model or technology can be inverted and simulated under the same conditions. This enables direct comparison of solutions.

Lastly, due to the solution dynamic, simulator can represent iteration between the product or impact of development process on product performance. This enables decision-makers to have a clear picture about the product current states and the potential improvements.

In the current version, the tool doesn't offer any solution for risk trade-off since this has been considered out of scope from the beginning of this work. However, due to the highly modular nature of the developed solution and the fact that the solutions are available in time frame and from every product element, the results can be implemented in customized or standardized decision-making approaches.

# 5. Illustrative example of the proposed solution

In order to provide deeper understanding on solution functioning, use and result, the approach has been applied on an illustrative example of a hair dryer design. The hair dryer has been decomposed as in (Hamraz et al., 2012). The data that was missing has been created to enable simulation. The hair dryer

is a simple product made of fan, motor, heating unit, power supply, control unit and casing. Its list of functional, behavioural and structural elements is presented in Table 3.6. The corresponding links between the elements are presented in the form of multi-domain matrix in Figure 3.18. Child nodes for every product element are represented in rows. Product element parents can be seen in columns.

Туре	ID	Description	Value	Туре	ID	Description	Value
Function	F0	Generate air flow	0,95	Behaviour	B12	Casing aerodynamics	0,95
Function	F1	Generate heat	0,91	Behaviour	B13	Casing heat	0,91
Function	F2	Mix air flow/heat and focus hot air flow	0,94	Structure	<b>S</b> 0	Fan geometry	0,95
Function	F3	Control level	0,90	Structure	<b>S</b> 1	Fan material	0,91
Behaviour	B0	Fan rotation	0,95	Structure	S2	Fan surface	0,94
Behaviour	B1	Fan aerodynamic	0,91	Structure	<b>S</b> 3	Motor geometry	0,90
Behaviour	B2	Fan heat	0,94	Structure	<b>S</b> 4	Motor material	0,95
Behaviour	B3	Fan noise	0,90	Structure	S5	Motor control	0,91
Behaviour	B4	Motor rotation	0,95	Structure	<b>S</b> 6	Power supply control	0,94
Behaviour	B5	Motor electricity	0,91	Structure	<b>S</b> 7	Heating unit material	0,90
Behavior	B6	Motor noise	0,94	Structure	<b>S</b> 8	Heating unit control	0,95
Behavior	B7	Motor weight	0,90	Structure	<b>S</b> 9	Heating unit geometry	0,91
Behavior	B8	Power supply electricity	0,95	Structure	S10	Control system control	0,94
Behavior	B9	Heating unit electricity	0,91	Structure	S11	Casing geometry	0,90
Behavior	B10	Heating unit heat	0,94	Structure	S12	Casing surface	0,95
Behavior	B11	Control system electricity	0,90	Structure	S13	Casing material	0,91

Table 3.6 Decomposition and value severities of a hair dryer

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Figure 3.18 Multi-domain matrix of a hair dryer

Due to the illustrative nature of a presented example, a simple problem has been studied. Since for conventional hair dryers technology and requirements are considered well-known, their severities for all the product elements are set to 1. Hence, in Table 3.6 only value severities are presented. This can

be explained that although the design environment is considered stable there is always a place for an error in the design task.

It is also considered that the strength of links is equal for all the elements. This leads to uniform distribution for problem and solution propagation. On the other hand, different sensitivity scenarios are tested: 1 and 0.1 for all links.

Regarding the model dynamic it is assumed that the agent is spreading the problem every 3 time units. The solution is spread every 6 time units in solution spreading state and every 5 time units in finished state. Different scenarios are tested for solution apparition. In the first scenario the first solution appears 40 time units after the problem. In the second scenario this delay is set to 20 time units. Iteration productivity is set to 20%. The element is considered as finished if its performance value is at least 0.98. In this example all the mentioned values are set randomly. However, in the case of the real product development they can be obtained by studying average number of problems and delay between the problem apparition and its solution. Based on the collected statistics, the information can be represented in the form of rates.

One model simulation run is documented in Figure 3.19. It shows propagation of problem appeared on element S0 and its corresponding solution.



Figure 3.19 Illustration of one propagation path

The problem is initialized at the beginning of the simulation at 0 time units (see Figure 3.19a). From this moment on, the problem is spreading on other product elements as it can be seen in Figures 3.19b and Figure 3.19c. After 40 time units, the solution to S0 has appeared as illustrated in Figure 3.19d. Hence, problems and solutions are now spreading together. In case of product development process this can appear when the problems are not fully determined and when information between different designers or teams is not synchronized. Hence, problem that has been solved can go back to problem spreading state due to the connection with agents in that state. The same happens in product development when different problems appear, and they concurrently influence product element. Also, the solution can simulate an iterative behaviour of design. In order to obtain proper solution, designers often change their designs. Change in one element leads to another. This can lead to iteration between several elements. Finally, when the problem is solved, and the values are satisfactory (greater than 0.98) the product element moves to finished state. Hence, at the same moment, certain agents may be finished, other solved and other in problem spreading state (see Figure 3.19e). Finally, the simulation stops when all the elements are finished (see Figure 3.19f). Also, the simulation stops if predefined time limit is overrun. Hence, the solution can capture the situations in which the finished state is not reached by all the elements.

View on more general product behaviour can be obtained using Monte Carlo simulation. Since no desired error has been set for this problem, the number of runs is limited to 1000. This analysis can give information on critical component, problem reoccurrences, lowest risk value, but also the testing of different scenarios.

Critical component can be determined based on the highest problem recurrence or based on the lowest performance. For the observed example, the highest reoccurrence is achieved in 60% of cases by F0 and in 30% of cases by S0. S0 is the element where the problem has started and F0 is the function that can be related to it. S0 represents fan geometry and F0 is the function for air flow generation, hence it is no surprise that they are related. Hence, the tool can be used like FMEA to identify the failure modes and effects. In this case no particular knowledge or scenario generation is necessary. Also, it can be said that the idea where the problems are firstly seen in the main functions can be proven with these results. Having the most common reoccurrence in the function related to the initial problem.

The second manner to identify critical component is by observing the lowest performance. In this metrics, further product analysis is necessary since the lowest value have been achieved by F1, F3, S0 and B7 in 10% to 30% of cases. Hence, it can be said that the connections (and initial values) may play a part in achieving these results.

Having identified the critical component, the general number or reoccurrences and lowest values are interesting to study. They are presented in Figure 3.20a and b, respectively.



Figure 3.20 Obtained results: a) maximum reoccurrence; b) minimum performance risk achieved

The reoccurrence represents the number of times the same element has entered problem spreading state. In Figure 3.20a the highest reoccurrences obtained in 1000 simulations are presented. The achieved mean value is 35.7, and the highest is going to over 170. This metrics shows how many error corrections or planned/unplanned iterations the design process may have. Having in mind that the example analysed here is academic, the actual results may vary. Anyhow, the tool can be used to show the potential cycle of try and error based on the current technology, requirements and quality of design tasks.

The lowest achieved performances are presented in Figure 3.20b. This metrics can show how risk prone the observed product is. As it can be seen in more than 50% of cases performance vary between 0.66 and 0.73. Hence, the average is 0.58. However, in 10% of cases performance is getting close to zero and in 1.8% it reaches it. Hence, the severe problems can be reached even when the initial conditions are not severe (0.9 and more of value severity). From the user perspective, it is useful to analyse the cases that lead to these severe outcomes and to implement measure to avoid them.

Finally, the solution support analysis of different scenarios in order to have a view on the influential factors in different conditions. In this example different solution delays, problem spreading rates and sensitivities were studied. The solution delay was either 40 or 20 time units after the problem apparition. Problem has been spread every 3 or 6 time units. Sensitivity was either 1 or 0.1 for all connections. The scenarios and their results are shown in Table 3.7.

Delay / problem spreading / sensitivity	Max recurrence	Min performance achieved	Number finished	Time finished
40/3/1	35.66	0.58	31.86	523.37
40/3/0.1	35.88	0.89	32	392.94
40/6/1	8.82	0.66	32	157.2
40/6/0.1	8.95	0.89	32	157.27
20/3/1	37.91	0.57	31.88	508.4
20/3/0.1	40.4	0.89	32	386.56
20/6/1	9.73	0.66	32	143.34
20/6/0.1	9.79	0.89	32	145.19

#### Table 3.7 Scenario comparison

The table shows that the best results are achieved with the delay of 40 time units, lower problem spreading rate (6 time units) and lower sensitivity between elements (0.1). As it can be seen in the table, the sensitivity has a direct influence on the performance value, which is no surprise. It also guaranties that all the product elements will reach their finished state due to the fact that the number finished is always equal to 32 with the lower sensitivity. The lower problem spreading rate (6 time units) lowers recurrence and time to finish. Lastly, better results are not achieved with the lower solution delay as it might be assumed. This can be explained that after 40 time units the problems have already significantly progressed and hence there is not too much space for further progression. Hence, when the solution appears after 40 time units, its efficacy is higher leading to less recurrences and shorter times. In terms of design management, this type of analysis can be useful in determining the proper problem-solving strategies. Hence, in this particular example it might be better to let risk spread before finding the solution. In other words, it is better to firstly investigate possible risk impacts.

The presented scenarios are just one of many that can be tested. Hence, this illustrative example has shown several possibilities for analysis: critical component, recurrence, performance values, sensitivity influence and others. Although the results here are not to be taken as is, due to the illustrative nature of a problem, clearly the solution presented in this chapter can be a powerful tool for decision-makers.
# 6. Risk management for product under development – conclusion on the performed work

Proposed solution provides a mean to address product performance risk during a development process. The main idea has been to represent the propagation of different risks from one product element to another. The solution based on FBS linkage, modified SIR simulation and agent methodology has been developed to actively consider process iteration and task, technology and requirement uncertainty. The combination of different approaches enables problem and solution spreading which leads to dynamic change of product performance.

From the user perspective, the main contribution of the developed solution lies in the dynamic evaluation and prediction of product performance risk. However, since the solution has covered the analysis step of risk management, certain contributions can be found in this area. In traditional risk analysis, the accent is usually put on risk representation and establishing the relations between the risks. In this approach, the risk analysis is based on drivers that are known to designer (design task, requirements and technology). Hence, the required information is directly based on the data that the designer usually considers. Risk relationships are not directly requested. Rather than that, the propagation of risk is based on the general connections between product elements. Hence, with this method, the main goal has been to put risk management one step closer to design process. In that sense, two processes are performed together and not independently from each other.

Having all the mentioned in mind, the contributions are the following:

- The presented solution forms a model based on drivers (task, requirements and technology uncertainty) and FBS linkage to enable performance risk representation and interaction
- The propagation of risks includes two flows: problem and solution represent dynamic changes in the product. Together with the proposed modified SIR simulation, the solution enables prediction and evaluation of a product performance in a timely manner.
- Different risk drivers and their influence can be simulated at the same time.
- Having in mind that the solution is based on stochastics, no knowledge nor scenario is needed for risk identification. Hence, the model can be used to prepopulate FMEA information.
- Powered by Monte Carlo analysis, the solution becomes powerful decision-making tool.
- The tool supports identification of critical components, reoccurrences, iterations and performance levels.
- Different product modules of a same product can be simulated and directly compared due to the modular nature of a solution.
- No solution of similar comprehensiveness has been identified in the literature.

In terms of perspectives, several axes can be made. Solution currently considers implicitly different link types between product elements. In other words, product elements types determine the connection type. It would be beneficial to investigate different systems to identify if different links (problem types) are necessary. Anyhow, they can be present in parallel and used for different risk propagations. The solution already supports propagation and representation of different link types. However, the research needs to be conducted to determine the need for them.

Other research axis can be in identification of problem root causes. Currently, the solution evaluates the influence of individual drivers on the product. However, it is not made to find possible root cause of a given performance. It would be interesting to investigate how model can be adapted to answer this kind of questions.

Lastly, the future work should be oriented towards data collection. On one hand, the connection between the solution database and CAD software and/or bill of materials can be used to ease the creation of the product network. On the other hand, data mining or statistical approaches can be used to prepopulate

necessary information. Also, if need be, the solution can be extended to include optimization or decision-making in a more direct manner.

The following chapter presents integrated process-product solution based on the two approaches shown in chapters 2 and 3.

# Chapter 4: Operational framework and simulator for global risk management in product development

#### Abstract

The fourth chapter of the thesis presents integrated process-product risk management solution for product development. It is based on individual process and product solutions presented in Chapter 2 and 3, respectively. Two initial models are adapted to enable joint risk management. The development tasks are divided by types according to their influence on product and connected to one or more product elements. Additional states are implemented to enable modification based on the risk values of both process and product. Product element is in direct contact with its development task. It can require modification if its performance risk is unsatisfactory. Hence, the global process-product risk model enables simultaneous calculation of risk on process and product level. In this chapter, the general need for this solution is elaborated in the first section. Framework, model, software solution and utilization are presented in the sections to follow. The solution is illustrated using an example of a hair dryer development. Finally, chapter ends with a conclusion.

Process risk have been studied in Chapter 2 and product risk in Chapter 3. However, none of the proposed approaches could answer the following questions. How vendor quality impact the product performance? How the interactions between product parameters, impact time and cost risk? Or, more globally: How change on product level impacts process risk and vice versa?

Although both solutions have shown certain level of comprehensiveness trough their behavioural interactions, none of the risk related question that considers both product and process behaviour can be answered using the individual solutions. Hence, the main goal of this chapter is to enable coupled process-product risk management.

The chapter is organized in the following manner. The first section focuses on the current state of the art and the need for the integrated risk management solution. Section 2 proposes framework and model for comprehensive solution. In Section 3, software solution developed based on the previously shown model is presented. Solution utilization in the context of risk assessment is explained in Section 4. The illustration of the solution is performed on the development of a hair dryer and presented in Section 5. At the end, the chapter is concluded with Section 6.

## **1.** General risk management in product development: call for action based on the state of the art

The literature analysis conducted throughout this thesis has identified several issues that characterize risk management in product development. These problems are firstly summarized in section 1.1. After, the connection between risk management and design has been explored to provide new perspective to the observed issues. Finally, a possible direction for general risk management solutions in product development has been proposed in section 1.3.

### 1.1. The problem in a nutshell

In the first three chapters, three different studies on risk management have been conducted. In Chapter 1, the focus was on general risk management in engineering. Chapter 2 had a goal to identify processoriented solutions that can be used in product development. Finally, in Chapter 3, approaches for product risks have been studied. All three studies have indicated the lack of connection between process and product-related approaches. This problem has also been indicated in the literature by Eckert et al. (2015). Cooper (2003) in her critique on the current risk management practice advocated for the connections between the "thought worlds". Hence, the need is still there – confirmed by the literature resources and the practice.

The product is integral part of every development process and the process is the one that shapes the product. Observing the two apart separately is an approximation that can cost a lot. If we go back to the first chapter of the thesis and Takata and Airbus examples, it is obvious that the integration between the process and the product risk management is necessary. In Takata case, the main reasons for the product recall has been explained by unstable chemical, defecting manufacturing practice and flawed quality control. In Airbus case, the installation cables have been designed short due to the lack of synchronization between the development teams. In both cases, flowed product has been made mainly due to the process issue. Although it can be said that these examples don't exclusively represent the rule, the need is still there. Undoubtedly, if Takata could estimate the impact of the faulty test on their product, the quality control would surely be enhanced and not suppressed as indicated in certain studies

on the case. Similarly, Airbus would do everything to avoid snowball effect of something as simple as coordination between teams.

It would be false to say that the effort is not made in terms of integration. However, as Eckert et al. (2015) emphasize, even the integrated solutions are based on either product or process. Hence, the other is obliged to accommodate to the main solution. Also, in practice, the risk management is mainly based on standards (ISO 31000 and 31010). Interactions within and between product and process are to be addressed using Bayesian networks, business impact analysis, event tree analysis, fault tree analysis, cause-consequence analysis, Markov analysis, Monte Carlo simulation, causal mapping or cross impact analysis. In ISO 31010 these approaches are not classified based on their usage in different domains. However, certain are more often seen in one of the two areas. In that sense, event and fault trees and their combination (cause-consequence analysis) are often classified as one of the main tools for product failure analysis. On the other hand, business impact analysis is clearly more related to process. For other approaches it can be said that they can be used in both domains.

Another issue that is imposed through the conducted literature reviews is the usage of different approaches. Especially in project domain, the focus is mostly on interactions between the individual risks. In that way, the behaviour of the development project is often left untreated leading to partial risk analysis. Without the systemic view on risk, certain events are uncovered since "extreme events can be a result of the inherent system dynamics rather than of unexpected external events" (Helbing, 2013). The previously mentioned approaches are focusing on consequence and likelihood. Although this doesn't necessarily imply that the only possible aspect to represent are individual and independent risk events, this is often the case. Inclusion of individual risk events and behaviour often requires combination of different approaches. Hence, mostly in product literature, the system engineering and standardized approaches are aiming at both product behaviour and individual risk events. Similar development is seen in the project area as well, but not so often.

To conclude, the adequate solution needs to suit, both, a process and a product and it has to cover behavioural aspects and individual events. The main question that needs to be answered is: *How to address risk interactions to enable comprehensive product-process view?* 

### 1.2. Risk management and design process

Talking about a development risk and not considering the design theory, might be a reason for over or underestimated risk that can be seen in practice. Observing a development process thorough the project provides only one perspective since all the processes (including risk management) are considered inferior to the project management (Project Management Institute, 2013). In other words, project management considers product risks, but it's not focused on them. In the product domain, the focus is almost exclusively on product and failures. Although risk management is not "picking sides" between a project and a product, for majority of solutions the focus is on one of them.

Contrary to the risk management, design theory is not making a gap between different aspect. Hence, the focus can be on: organization (Pahl et al., 2007), product (Gero, 1990) and design activity (Weber, 2007). Organization-oriented approaches are similar to the "pure" process approaches. Product solutions are dealing with the product only. Design activity connects the two worlds – it maps activities performed by a designer to product characteristics. Hence, if risk management is made around design activity, the process-product interaction can be considered. How risk management and design theory can be related is shown in Figure 4.1.



Figure 4.1 Design and risk management

The bottom of the figure illustrates risks that have been considered in this thesis and in majority or risk related literature. The risks can be firstly divided into process-related and product-related. After, within each category, different output risks can be observed. Cost and time issues are most often considered in project risk management. In this thesis, apart from the mentioned, process performance risk is also considered. Product risks include performance, technology and requirements. However, the appearance of a risk in one domain can provoke risk in the other. Low product performance requires additional work to attain the desired quality level and this leads to schedule and cost risk. If the development process is risky, it directly impacts the product causing potential product performance risk management is that they can cover only one aspect. Hence, the interactions between the process and the product are left untreated.

In the design domain, organization-oriented design deals with the design tasks and their interaction in the similar way as the process-oriented risk management. Product design approaches are describing the product. Hence, they can be compared to the product-oriented risk management focused on product only. Design activity connects organizational and product approaches. It starts from the engineering activity that is essentially organizational and maps it to product characteristics. Hence, if the process risk is divided into task and maps to the product elements, the connection between the two "worlds" can be made. In other words, the connection that is created between the process and product risk is not arbitrary but based on the essential process – design. More details on proposed solution are presented in subsection 1.3 and Section 2.

### **1.3.** The solution direction

Discussing about globally connected risk, Helbing (2013) states that the system science may provide adequate paradigm shift and knowledge. Moving to socio-technical system, INCOSE Model-Based System Engineering initiative addresses not only product but development process using system

engineering (Estefan, 2008). Similar observation can be found in global NASA (*NASA Risk Management Handbook*, 2011) and US Department of Defense (*DoD Risk, Issue, and Opportunity Management Guide*, 2017) frameworks. In the first document, the system engineering is observed as a base "that is used to drive the development of the system and associated work product to satisfy stakeholder expectations in all mission execution domains including safety, technical, cost and schedule." In the similar way, US Department of Defense defines system engineering activities through their product or project focus.

New tendencies clearly identify system engineering as a key solution around which risk management can be organized. This has been shown through the major frameworks, but also through the literature surveys in Chapter 2 and 3 where system engineering approaches were significantly present. Hence, the solutions presented in this thesis are based on system engineering. Process-related solution clearly decomposes development into activities and patterns as in MBSE. Product-related solution is based on product decomposition and connections between the components. The detailed relations are not directly considered since the goal has been to enable risk management for the whole life cycle. Having detailed information related to relationships in conceptual phase is usually not the case. Hence, the relations are mainly architectural. However, the solution enables further development and inclusion of flows like in system architecture models.

Although solutions proposed in the thesis are made with the other aspect in mind (product solution considers development process and vice versa), this is just a step towards comprehensive process-product risk management. The proposition for comprehensive process-product risk management solution is shown in Figure 4.2.



Figure 4.2 Proposed general process-product risk management solution

The solution is divided into MBSE model (see 1 in Figure 4.2) and risks (see 2 in Figure 4.2). Based on the conducted literature and performed works during the thesis, it is believed that the system engineering can provide adequate behaviour description and that standardized risk approaches can enable consideration of individual risks. Captured risk are mapped into system parameters (3 and 4 in Figure 4.2) from which they progress further into system using the behavioural models. System engineering enables all behaviour-related processes – from a development process (see 5 in Figure 4.2) to product (see 6 in Figure 4.2). In the thesis, these processes include process and product solutions and their connection. Hence, the idea is to have clear distinction between behavioural aspect of risk and epistemic risk. Epistemic risks are represented through their individual events and modelled using standardized approaches (like Bayesian network). Hence, risk management approaches are used for effect identification on project and product parameters. The main flexibility lies in the fact that different

approaches can address different parameters. Thus, the solution decomposed into system part and risk approach part can be suitable for different users, scenarios and available information.

Having in mind that the process and product models have already been developed, the question is how they go together. As it can be seen in Figure 4.1, special attention has been made to process-product connection (see 7 in Figure 4.2). Rather than being a separate model, process-product connection preserves the two separate models and merges them into one. This is considered important since Eckert et al. (2015) emphasize that one of the problems associated with the integrated models is their orientation to either process or product. Hence, in this thesis it is believed that the appropriate connection can be enabled though design.

Design theory is oriented towards organization, product and designer. As emphasized in Section 1.2, the connections can be made between the risk management and approaches in design. Organization-related design approaches observe design process globally. They are, hence, similar to the risk management observing the development process in a global manner. Design approaches in product domain target the same characteristic of a product as in risk management. Risk management observes failure of a product through its components, failure modes and functionality lost. Design theory aims at defining product based on their components, architecture, structure, behaviour and function. Hence, like seen in Chapter 3, design theory like FBS can be used as a base for product risk management. Having in mind that these two risk and design views are rather static, they observe risk through gates or stages. Weber's designer-oriented approach can provide the needed dynamic. Firstly, this approach can decompose development process to include interactions and stakeholders like presented in Chapter 2. Secondly, this action-driven approach provides a base for process-product integration. This connection is presented in Figure 4.2.

The process is decomposed into tasks, each of which has its deliverables (8 in Figure 4.2). The product is decomposed, as well, and possesses its deliverables (9 in Figure 4.2). All deliverables can be mapped into process-product connection (see 8 and 9 in Figure 4.2). This connection enables "crossing" of the influence from process to product and vice versa. As indicated in design theory, design task clearly defines the work performed by a designer, but also impacts the product. This is the core of process-product connection. Process deliverables are matched with the adequate product element. Thus, process influence can be defined for every product element (see 10 in Figure 4.2). As a reaction to this influence, but also due to the other reasons, product deliverables are formed. Similarly as process ones, they can impact certain process tasks (see 11 in Figure 4.2). This way, without changing the individual process and product solutions, an integrated process-product model is established. Its details are presented in the following section.

# 2. Global risk management in product development – the proposed framework and the model

This section presents the main idea and the global framework for risk management solution in product development. The idea is based on the process (Chapter 2) and product (Chapter 3) solutions. Thus, in the section 2.1, the focus is on the integration of the two aspects. The framework presents connection based on the design theory. In that sense, the framework presentation in section 2.3 is introduced with a short explanation related to the used design framework from the literature (section 2.2). The framework is followed by the developed model in section 2.4. The chapter is finalized with the conclusion.

### 2.1. Global risk management in product development - the idea

The main idea of this global risk management solution is based on the connections between the process and the product. This is illustrated in Figure 4.3.

As it can be seen in the figure, the problem is decomposed into process, product and their connections. Both, process and its product, consider independent and dependent risks. Independent risks directly impact only process or product (see 1 in Figure 4.3). On the process level, these risks include individual risk events that impact behavioural parameters. Shutdown of factories due to the pandemic can cause certain supplier to be unavailable. Hence, this event directly impacts "vendor reliability" parameter of the process model. The mentioned event doesn't impact the product directly. As explained in Chapter 3 and based on Browning's work, independent and direct influence on a product includes technology and requirement uncertainty.



Figure 4.3 The idea behaving global risk management solution

Processes are made of activities. Network of activities form process behaviour. Although, both, an activity and a product behaviour (see 2 in Figure 4.3) is represented through nodes and connections between them, the risk influence is not limited only to its direct impact. Hence, by affecting one node, the risk can propagate through other nodes using the connections between them. As an example, technology risk of a component may cause technology issues in the related components. In the case of process, the risk impact one activity, propagates through its behaviour and, after further into process behaviour. Hence, in both product and process, the risk propagates from direct to indirect. But, this

propagation is not bounded by a process or a product. The risk can cross the borders that exist between the two.

Each design activity defines one or more product elements (see 3 in Figure 4.3). Hence, when the risk impacts an activity, its influence can affect product element as well (see 4 in Figure 4.3). Poorly performed design task, can lead to problems in product functioning. Similarly when the product element is affected, the corresponding activity is affected as well. If it is identified that the chosen technology is not performing as desired, additional designer effort is needed to solve the issue. Hence, activity risk is impacted.

The process output risks and product performance risk (see 5 in Figure 4.3) may just seem independent. Through the interconnection within and between process and product, the resulting risk is more a stable state of a highly connected system. Hence, the main idea presented here aims at representing this connectivity and quantifying its overall influence. The framework that support the idea is introduced in the following subsections.

### 2.2. Global risk management in product development – FBS framework as a background of the proposed framework

The concept of activity connection is very traditional – past actions influence future ones. Contrary to this case, an adequate representation is needed to illustrate product information from the activity perspective. This representation must be in accordance with the product nature. Undoubtedly, it should reflect process influence. To perform this, in Chapter 3, FBS linkage model has been used to decompose and illustrate a product. Since this representation is based on the FBS framework proposed by Gero (1990), it is considered essential to cover it in more details. In this subsection, modified FBS framework is presented to enable connection between the process and the product.

FBS framework represent product transformation from its functions into a design description. These transformations are performed during a design process. Generally speaking, product functions form desired product behaviour based on which product structure is synthetized. The structural representation forms design description through detailing. However, this process is not straightforward. Before embarking into details, designed product behaviour (Bs) needs to be determined and compared to requirements. Having in mind this structural behaviour (Bs) and expected behaviour (Be), desires and developed product can be compared. If needed, different product aspects can be reformulated to adequately address requirements.

In the modified FBS framework (Figure 4.4), all Gero's representation stages (Function (F), Expected Behaviour (Be), Structure (S), Behaviour of the structure (Bs) and Description (D)) and processes/activities (formulation, synthesis, analysis, evaluation, reformulation and production of design description) are represented. However, the additional representations and details on the processes are introduced. This includes:

- Introduction of requirements
- Introduction of generic structure
- Observations of Gero's structure processes that can be decomposed into activities.

Requirements represent the connection between the product and the targeted customers and market expectations. Success of the product and its development process is often measured based on the market adoption and other factors that are highly customer related. Consequently, requirements drive numerous processes (activities) and define the final product. As seen in Chapter 3, they are also an important factor influencing product performance (Tyson R. Browning, 1998). Their inclusion into the FBS

framework is discussed and performed in the literature from the customer perspective (Cascini et al., 2013) and from the perspective of knowledge representation (Christophe et al., 2010). The two views confirm the necessity of the requirements and in that sense justify their inclusion in the thesis from the perspective of a design process. Knowledge management perspective also relates FBS (or more precisely the RFBS) to MBSE which is significant since the system engineering has been identified as the core of a process and product behavioural models. Consequently, connection between FBS and MBSE is already confirmed in the literature. This forms the base for the advancements in the direction of comprehensive process-product risk management.



Figure 4.4 Modified FBS framework

Introduction of a generic structure is directly connected to one of the guiding ideas of the thesis. As stated before, the main goal of the thesis is to provide a global risk management solution. The comprehensive tool, that is presented throughout the thesis, needs to be supported by the proper knowledge management. And while the connection has already been made with the MBSE, the support needs to enable encapsulation of proper data. Hence, in Chapter 2 the solution is developed as a pattern. Introduction of a generic structure means that the data can be related and saved in a product structure and used as needed. Christophe et al. (2010) have already introduced this approach into FBS framework and model-based engineering. Here the authors have used the generic structure to encapsulate function and their intrinsic attributes. In the thesis this information is risk related. Hence, the knowledge of the

particular risk management problem can be applied and updated each time the component is used. And this is true on, both, process and product levels.

The Gero's design processes/activities are clearly described but not further analysed in the original article. Howard et al. (2008) have analysed FBS and divided the design transitions based on the creativity. Consequently, formulation, synthesis and all reformulations belong to the generation stage of the creative process while analysis and evaluation clearly correlate to the evaluation phase of the creation process. And while this is no surprise and can be considered common sense, it is interesting to analyse the activities a bit deeper. Cascini et al. (2013) have decomposed some activities into subactivities. While synthesis and analysis can't be further decomposed, the formulation and reformulations can be. Formulation includes analysis, synthesis and choice and reformulations only includes analysis and choice. From the thesis perspective, this way of presenting is significant for two reasons. Firstly, even though the goal of the activity may be to generate new solution, this task needs to be supported by the proper information to drive it. Hence, synthesis (and choice) depend on the quality of the analysis and on decision-maker's abilities and preferences. Secondly, transitions between stages in FBS framework can be directly represented through processes and activities. With the clear purpose, each part of the transition can be related to one or more design tasks. Consequently, design activity driven process can be applied and used to create comprehensive process-product risk management approach.

Considering all the elements of a modified FBS, the solution framework is presented in the following section.

### 2.3. Global risk management in product development – the framework

The proposed framework uses modified FBS to map product and process risk management. Figure 4.5 illustrates the framework.

The framework distinguishes following product elements: requirements (R in Figure 4.5), functions (F in Figure 4.5), behaviour (expected Be and designed Bs behaviour in Figure 4.5). Although detailing is considered as a final stage of a product, it is not considered in this framework. Functions, behaviours and structures can adequately describe product for the needs of this thesis. Additionally, the framework supports generic structure (Gs in Figure 4.5). Hence, the product can be partially or fully made of predefined components with the known risk characteristics. It is necessary to emphasize that F, B and S represent the set of functions, behaviours and structures and not only one element. Hence, the global framework is based on the product solution presented in Chapter 3. Requirements role in the proposed framework is to describe uncertainty of the product. Hence, they are not considered as a separate product element but as an attribute. R, F and Be are all describing the desired product. Hence, S and Bs show how the performances of a product under development are aligned with the customer needs. This is also in accordance with previously presented product solution (Chapter 3) and its requirement risks.

Process representation is based on FBS transitions. In order to "move" a product from one aspect (F, B or S) to the other, the transitions need to be executed. The only way to perform the transition is by performing adequate design tasks. Hence, every process activity can be related to one transition and one or more product elements. While all activities are directly related to their transition(s), certain activities are only indirectly related to product elements. The product element goes through changes with every executed function that is directly or indirectly related to him. However, it is assumed that the risk propagates once the whole transition is performed.



Figure 4.5 Proposed framework for global risk management in product development

As an example, to synthetize proper material of a heating element of a hair dryer several tasks need to be performed. Firstly, the group lead explains to a designer requirement details. The designer synthetizes the acquired information and proposes the material based on his or her experience. In the third stage, the designer and the team lead verify the choice. In case of approval, the information about the material choice is communicated further in development process. Hence, although the heating element material has been modified by every action performed, the risk induced by all three tasks can potentially propagate only after the final choice is made. Hence, in terms of risk propagation it is always the last activity of the transition that triggers the propagation. This activity is considered to have a direct influence on a product element. It is necessary to emphasize that previously defined product element can be modified in different activities. For example, heating unit material may be changed after the tests. Hence, different transitions and their activities impact product elements risk and provoke potential modification on the product elements. These modifications can be planned and performed in the special task or they may indicate the need to redo previous tasks or group of tasks.

The illustration of activities performing a synthesis and an analysis task is shown in Figure 4.5. As it can be seen, based on the desired behaviour (1 in Figure 4.5), one or more structural elements (see 2 in Figure 4.5) are defined. What development activities are carried out depends on the project planning and structural elements affected. Consequently, the activity performed is derived from the list of the

activities to support the synthesis process of a structural element(s). Hence, at least one activity is dedicated purely to synthesis or creation of a solution. Other activities can support the creation of the structural element. For example, if designer needs additional information, an analysis task will be performed to collect the information. Also, if the approval is needed after the creation of a structural element, the choice task is performed. This was the case in the example of a heating unit material. Detailed information about the type of activities is presented in Section 2.4.1.

As seen in Figure 4.5, in order to create structural element from expected behaviour two activities are performed. The first activity (see 3 in Figure 4.5) impacts the second one (see 4 in Figure 4.5) through precedence relationship. The first activity impacts the risk value of the defined structural element, but it doesn't trigger risk propagation. At the end of the second activity, the risk is changed again and propagated further into the system. Hence, the second activity impacts directly the product (see 5 in Figure 4.5). The propagation of risk may cause changes in risk levels on the same or different product element – behaviours and functions. Since all these elements are related to adequate activities, the risk propagation chain can lead to the change in risk levels for different activities. As an example, if due to the propagation, functional risk is considered unacceptable, activities need to be modified to compensate the risk. All the impacted activities need to be redone. This leads to the change in values of their process risk.

It shouldn't be forgotten that the influence of one activity is not limited to its transition and the product it defines. Information obtained from the second activity of synthesis transition (see 4 in Figure 4.5) can be used in the other activities of a development process. The connection between this activity and other activities is again defined through the precedence relationships (see 6 in Figure 4.5). As it can be seen, the impacted activity can belong to different transitions (analysis in this case). Also, it can be related to the other product elements.

With all the mentioned in mind, the proposed framework supports risk management considering product and process interactions. The solution handles risk propagation through sequential relationships in the process domain. The product domain enables reciprocal relationships through the connection between different product elements. Since the global solution is based on the previously developed individual process and product tools, the proposed framework makes no trade-off between the process and the product. Detailed information about the solution are provided in the following sections.

### 2.4. Global risk management in product development - the model

The model is organized as the two-step process, Figure 4.6. Calculation of activity risks is followed by the calculation of product element risks. Activity influences the product through its value risk. Value risk acts as a parameter for other product elements risks. Hence, it influences product performance. Product element performance risk impacts the activity. If the obtained product performance is unsatisfactory, the activity needs to be redone. Every time the activity is redone its output risks are affected and recalculated.

This process-product loop repeats every time the change affect product or a process. The risk propagates not only between the process and the product, but also within the two. This risk calculation cycle repeats for all activities and product elements until the desired characteristic or until the best possible results are achieved. In any case, process output risks (time, cost and value) and product performance risk depend on each other and evolve together.



Figure 4.6 Proposed model for global risk management in product development

Calculation of activity risks is performed using the model and the solution presented in Chapter 2. Product risks are calculated using the solution from the third chapter. However, improvements of the two models have been made in order to enable synchronous calculation of process and process risk. These modifications are presented in the next three subsections. Firstly, in subsection 2.4.1 activity types and their influence on product are presented. Secondly, process model modifications are presented. are presented. Secondly, process model modifications are presented.

### 2.4.1. Activity types and their influence on a product

During a product development, stakeholders perform various tasks to produce a product with the desired characteristics. What activities are performed depends on the current development phase. The work in this thesis focuses on the first phase – design. The task types are, thus, suited for it. If the risk management solution is to be used in different development phases or for the product with specific development process, the activity types can be extended to suit them.

It has already been elaborated that activity needs to be mapped to transitions in the modified FBS model. Transitions represent the transformation of a product from one state to the other. The transformation is performed using the task and the associated actor. The transitions have been initially defined by Gero and further developed in other works (Cascini et al., 2013; Christophe et al., 2010; Howard et al., 2008). As seen before, in this thesis, the transitions are decomposed according to Gero (1990) and Cascini et al. (2013). According to this classification, design transformations and, consequently, development process can be represented using 4 activity types: analysis, synthesis, choice and evaluation. Their definition for the need of this work is presented in Table 4.1.

Activity type	Description	Influence on the product
Analysis	Transforms the available data into the information needed for the further development.	Impact value and requirements. Risk propagation is not provoked.
Synthesis	Emerges information and ideas into solution based on actors' knowledge and communication.	Impacts value and technology. Technology depends on current levels of skill, communication, organization and vendor quality. Can propagate risks.
Choice (or Synthesis-Choice)	Decides if the objectives have been obtained and picks the adequate solution	Impacts value and technology. Technology depends on current levels of skill, communication, organization and vendor quality. Propagates risks.
Evaluation	Measures the gap between the obtained and desired objectives (Godot, 2013)	Sets new values for the measured elements. Propagates risk.

Table 4.1 Activity types	their description and	influence on a product
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**Analysis** is an activity in which available data are transformed into needed information. Analysis can be part of formulation or performed whenever further information is necessary for the development process. The example of analysis task is the transformation of a market data into new product requirements. Analysis is also performed before creation of a new solution when requirements are translated into influential information for the product element in development. Analysis value risk impacts product value and requirement risks. The product sensitivity on the activity value variation is low. Hence, process-product sensitivity parameter is set to 0.3. The sensitivity value can be adjusted to meet the user needs and real analysis behaviour. New value and requirement risks are calculated using the following formulas:

$$Value^{new} = Value^{old} \cdot (1 - 0.3 \cdot AnalysisValueRisk)$$
(4.1)  

$$Requirement^{new} = Requirement^{old} \cdot (1 - 0.3 \cdot AnalysisValueRisk)$$
(4.2)

Hence, the new value of product risk factors depends on their old values and obtained analysis value risk. Analysis impacts product risk factors, but it doesn't trigger risk propagation further into system since it is often not the last activity in the transformation chain.

**Synthesis** is an activity where information and ideas are emerged to form a solution. This task depends on actors' knowledge, communication and organization. The example of synthesis activity can be any task where solution is created. Specification of a heating unit material for a hair dryer is a synthesis task. However, this task is often performed together with analysis and choice. Analysis provides necessary information and choice validates suggested solution. Product is moderately sensitive to the synthesis risks. The process-product sensitivity is set to 0.6. The sensitivity impact technology and value risk. Their calculation is based on the formulas:

$$Value^{new} = Value^{old} \cdot (1 - 0.6 \cdot AnalysisValueRisk)$$
(4.3)

$$Technology^{new} = Technology^{ola} \cdot (1 - 0.6 \cdot SynthesisImpactOnTechnology), \qquad (4.4)$$
  
where

$$SynthesisImpactOnTechnology = \frac{Skill + Organization + Communication + Vendor quality}{4}$$
(4.5)

Value risk is calculated in the same manner as in Analysis activity. The only difference represents the process-product sensitivity parameter which is set to 0.6 instead of 0.3. This value (0.6) is chosen to represent medium effect, comparing to the weaker influence (0.3). It can be adjusted if need be.

Technology calculation depends on current value of process-risk factors: skill, organization, communication and vendor quality. Communication is a factor that is present only if several actors are involved in synthesis task. Vendor quality appears only if vendor is partially performing the task. Synthesis triggers propagation of risks only if it is the last activity performed (no choice).

**Choice** is an activity performed to verify if the desired product objectives have been attained. Picking one among several possible solutions is a choice task. Similarly, validation of only one solution is also a choice task. In this case, the choice is not between the solution, but between "acceptable" or "not acceptable". Thus, choice often follows synthesis tasks. Product is highly dependent on this task. Sensitivity parameter is, hence, set to 1. Choice impact value and the same equation can be applied for its calculation. Only process-product sensitivity is set to 1 instead of 0.6. Being a place where decisions are made, choice always propagates risk.

**Synthesis-Choice** is a task where creative process is performed together with a choice. Hence, the risk calculation is the combination of the two previously described activities:

$$Value^{new} = Value^{old} \cdot (1 - AnalysisValueRisk)$$

$$(4.6)$$

$$Technology^{new} = Technology^{old} \cdot (1 - 0.6 \cdot SynthesisImpactOnTechnology)$$
(4.7)

**Evaluation** is an activity where the gap between the desired and obtained characteristics is measured. Hence, this activity reduces the uncertainty and sets different values of product characteristics. In the context of risk management, it is used to reset performance uncertainty.

After the activity influences have been defined, it is necessary to perform certain changes on the process model to enable proper functioning. These changes are presented in the following subsection.

### 2.4.2. Process model modification necessary for global risk management

The process model proposed in Chapter 2 considers activity redo or modification briefly. Since no product data is available, the only condition based on which the modification can be made, is the current value risk. With the process-product integration, modifications are triggered by product performance value as well. Performance risk is a result of its design task and the connections between product elements. Insufficient performance requires modification of the activity in order to improve the solution. This performance threshold is set by the user.

Activity under modification, improves its value based on iteration productivity. Iteration productivity is defined in the same way as in Chapter 3. It is the percentage of initial value that is improved. Activity can improve only factors that are activity-related: value, skill, communication and organization. Factors that are product-related are improved based on the new activity-related values.

Apart from iteration productivity, activity (based on its type) can trigger the propagation risk through the product.

### 2.4.3.Product model modification necessary for global risk management

Modified product model excludes all the aspect that are process-related and that were previously part of the solution. Iteration performance and, thus, problem resolution depends directly on the process model. The problems, on the other hand, can propagate from other product elements or from the associated activity. The rest of the product model is the same as in Chapter 3.

### 2.5. Conclusions on the proposed framework and model for global risk management solution in product development

The second section presents a framework and a model for global risk management in product development. One of the main goals of the solution is to enable integrated process-product risk management that is considered equally convenient for both areas. Hence, the framework and the model address previously developed process and product solution and provide a mean for their integration. The integration is based on a design theory and uses FBS framework as a connection layer. The process activities address FBS transition and perform product transformation. Transformation triggers product risk and this risk can cause new process risk. The outputs of the solution are the same as in previous chapters (process value, time, cost and product performance risk). They are the result of the risk interactions on process, product and process-product levels.

The process influences product performance using the quality of the performed activities. Products with the low performance require additional actions on a development level. These are the main connections that are captured in this general framework. While this process-product integration is general and in accordance with the real development, other elements of the proposed model can be adapted to suit the need of the user. Sensitivity and impact present only one possible way which can be used for influence calculation.

With all the mentioned in mind, it can be said that the main contribution of this integration is in its flexibility. The model enables process-product risk management with the equal attention of product and its development process. Contrary to the most solution in the literature (Eckert et al., 2015), no trade-off is necessary between the process and the product. As a result, model can capture complex risk propagation that include connection within and between the main aspects. The following section covers in detail how the framework and the model are formed into the software solution.

### 3. Global risk management for product development – the software solution

After the framework and the model have been defined, the software development is considered in this section. Firstly, general software organization has been presented in section 3.1. After, the structure of a software model is detailed. Lastly, process and product agent models are shown in sections 3.3 and 3.4, respectively.

### 3.1. General software organization

The proposed solution combines previously developed models into the whole. Hence, in terms of general software organization, it is a combination of previously developed models (Figure 4.7).

As it can be seen in Figure 4.7, the software solution can be divided in three parts. The external risk events are represented in the same way as in Chapter 2. Represented by Bayesian Networks (BN software), it is UnBBayes tool that is used to model external risks. External risks are generally process-oriented. Pure product risks are limited to technology and requirement uncertainties, hence, at this stage no risk network is planned for their representation and calculation. However, if the data exist, Bayesian Networks for product risk factors can be created in UnBBayes software. The obtained results from this tool are stored in the database. No direct connection between Bayesian part and the main software is needed. The collection of data necessary for network modelling is a long process. Hence, the connection between BN software, database and main solution can be establish before each simulation. Considering

that UnBBayes is an open source software written in Java, if needed, there is a possibility for the connection with the main software solution.



Figure 4.7 General software organization of a global risk management solution in product development

Database used in the global simulator combines process and product databases presented in chapters 2 and 3, respectively. Process database contains all the information about the risk events, activities, stakeholders, input, controls, methods, equipment, vendors, organizational factors and all the necessary connection. Product database enables product decomposition. Hence, it contains information about product elements and their connections. The connection between product elements and activities is also part of the global database. The database is made as an Excel file where different tables represent different information.

The main part of a global risk management simulator is developed using agent methodology in AnyLogic software. Since the independent process and product models have been developed using the same technology and the same software, only adaptation of the two has been necessary. The two solutions have been merged into one. All product and process agents are listed under the same coordination agent. The connections between the two aspects are made directly between them and without introduction of any new agents. These details are presented further in this section.

### **3.2.** Structure of a software model

The complete model structure is presented in Figure 4.8. It consists of the classes that are presented in process (Chapter 2) and product (Chapter 3) models and their connections, parameters and methods.

Each activity without redo or modification calculates its risk in the same way as explained earlier in the thesis. Activity has risk factors influenced by individual risk events that evolve based on the network between them and form final risks. Product model includes product elements and their links used for product decomposition. Each product element has its own performance risk. This risk influences other elements in the product by propagating through the network of links and elements.

In the global model, process model influences product model and vice versa. Hence, after initial risk calculation on process level, it is necessary to calculate risk on the product level. Section 2.4.1 has shown how an activity risk influences product performance risk. Process-product connection is visible in the structural model. Here, activity influences product element risk through its output risk. Activity

uses deliverProductRisk() function to calculate new values of performance risk. In case that activity can initiate risk propagation on the product level, propagateProductRisk() function is used. When this function is executed, the performance risk propagates on the product level using the links between product elements. This propagation is enabled using the riskPropagation() function of a product element. Each time risk propagates, new value is calculated using riskCalculation() function. New product risk value may lead to the modification on the process level. This is considered through the connection between product element risk and activity. The product element uses deliverModification() function to initiate modification on the activity level.



Figure 4.8 UML Class diagram of a global risk management solution

Generally speaking, process modification is necessary in two cases:

- If the activity value is low and
- If product performance is low.

Value is one of the output risks of an activity. Each time an activity is performed, value risk is updated. The activity verifies if the value risk is within the desired boundary and performs modification if needed. Activity uses its deliverModification() function to trigger the modification. Modification represents new iteration. Hence, affected risk factors are improved based on iterationProductivity and calculateModification() function. Each iteration updates product risk values in the same way as explained previously.

Not all changes in performance risks lead to activity modification. Similarly to value risk, if the performance risk is within the desired boundaries, activity is unaffected. If risk is out of the boundary, the modification needs to be performed. Product element informs associated activity using the deliverModification() function. The modification that is performed is the same as explained. Hence, only activity risk factors are improved using the iterationProductivity and product risk is updated accordingly.

It is necessary to notice that sometimes more than one iteration is necessary to provide satisfactory risk. In that case, activity re-enters modification as much times as needed. Consequently, numberIteration is updated every time modification is performed. The activity can enter modification after any other action – even after it has been finished. Also, activity re-enters modification even after modification. If new values are not satisfactory after the improvement defined by iterationProductivity and calculateModification(), new iteration is needed.

As it can be seen from the solution structure, product and process influence each other. The risk evolves through regular activities, their modification and propagation through both product and process. Hence, the simulator is capable to capture all the major situation that can be encountered during the product development. Those situations are captured using the behavioural model and through the individual risk events that are part of Bayesian Network. Consequently, with the adequate information from the user, the simulator can be used to predict various scenarios and their output risks.

The following subsections cover in detail, product and process models to enable full understanding of a developed solution.

### 3.3. Updated process model as part of a global solution

Process model has been explained in Chapter 2. Hence, the main goal of this section is only to present changes that have been performed to enable its integration into the global solution.

The main part of the process model is an activity agent. Each activity is related to one or more product elements. Activity agent is the only agent on which the changes have been applied. New statechart for this agent is presented in Figure 4.9. The statechart and the figure are used to illustrate new behaviour of the activity in the context of global risk management.

The activity agent can be in one of five states: inactive, active, finished, modifying and spreading. Two new states (modifying and spreading) have been added to the activity agent to enable easier synchronization with the product agent.

At the beginning of the simulation all activities are inactive. The activity moves to active state by receiving activation message. The first activity in the process plan receives this message at the

beginning of the simulation. Other activities are activated by sending messages between the agents. The precedence relationships, levels and orders are followed during the activation. This part of the model is identical as in Chapter 2.



Agent enters « modifying » state by receiving « modify ». This message can be sent to itself (in case that value risk is lower than 0.95) or by appropriate product element (in case that its performance risk is lower than 0.85). When activity is in modifying state, firstly, iteration number is increased by 1. Secondly, activity risk factors are improved based on the iteration performance. After, cost and time risk are calculated. Finally, product performance is updated. If value risk is greater than 0.95 agent moves to the « spreading » state. In case the value is inferior, the agent re-enters the « modifying » state and performs the whole process. The agent re-enters « modifying » state using the recursive connector.

#### Figure 4.9 Activity agent statechart

Once in the active state, agent collects all the relevant information about its risk factor and calculates their new values using Fuzzy Cognitive Map. Again, this state is the same as in the individual process model.

After new risk factor values have been determined, activity passes to finished state. Here, hazardous events are randomly applied to modify risk factors and form final output risks. Obtained value risk and current skill, communication, organization and vendor quality values are, then, used to calculate new performance risk for related product element(s). Activity value risk can directly impact only requirement and value risk of a product element. Skill, organization, communication and vendor quality

(4)

« Spreading » state is the final state

for the activity. In this state,

activity can (based on their type)

indicate propagation of risks on

product level. This state activates

next activities in the process plan.

impact technology risk. This calculation is in accordance with the model presented in section 2.4.1. Agent uses deliverProductRisk() function to perform this calculation.

The activity moves to "spreading" state if its value is greater than 0.95. This condition can be modified to different values to suit different needs of a user. "Spreading" is the final state and the goal state for all activities. Once in this state, the agent can trigger risk propagation on a product level using the function propagateProductRisk(). It shouldn't be forgotten that only certain activity types can propagate product risks. Finally, once the activity reaches this stage it can activate next activities.

If an agent receives modification massage, it enters "modifying" state. "Modify" is delivered using the deliverModification() if activity value is lower than 0.95. Also, if the product element performance is lower than 0.85, it is the product element that delivers modification message to its activity. For the activity, entering "modifying" state represents new iteration. In this state agent improves its value risk and other risk factors using the iteration performance and calculateModification() function. Also, cost and time risk are calculated. In the current version of the software, cost and time are determined as a random value within previously defined lower and upper boundaries. Hence, every time agent enters modifications state, the cost and the time values will be assigned to it. In this way, modification cost and time depend on the defined boundary and the number of iterations performance is calculated using the updated value and risk factors. The agent moves to "spreading" state if its new value is greater than 0.95. In case value is inferior, the agent re-enters "modifying" state using the recursive connection and the whole process is repeated.

### 3.4. Updated product model as part of a global solution

Same as process, product model has been modified to suit global risk management. Having in mind that the individual process model is addressing certain process aspect, in the adapted model these functionalities have been removed since they are considered by the activity agent. Updated product model is presented in Figure 4.10 using a product element statechart.



At the beginning of the simulation, product elements are in « susceptible » state. First problem is propagated from the activity level, product element is in « susceptible » state.

Product element enters « problem spreading » state by receiving « problem ». This message can be sent either by activity or by other product element. First product element is entering problems spreading state by receiving the message from its activity. Agent in this state spreads the problem to at most one random agent. If its performance risk is lower than 0.85, product agents informs activity that the modification is necessary. This is performed by sending « modification » to its activity agent.

Product element moves from « problem spreading » to « solved » state if its performance is higher than 0.85. From this state, product element can go back to « problem spreading state ».

Figure 4.10 Statechart of a product element agent

Initially all product elements are in "susceptible" state. They can stay in this state although their performance risk is updated. This is due to the fact that the first problem spreading needs to be triggered by the activity. Although all activities impact product performance, not all of them can initiate risk propagation. Once the first product element moves to "problem spreading" state, the risk starts to circulate through the product. Agent in the "problem spreading" state propagates the risk to at most one random connected product element. Hence, product elements can enter "problem spreading" state either due to the activity or due to the propagation of risk from another product element. With every propagation, new product performance risk needs to be calculated. The calculation is performed using riskCalculation() function. If the agent is infected while in the "problem spreading" state, their risk is recalculated in the same manner. If the value of performance is lower than 0.85, product element performs deliverModification() function and informs its related activity that the modification is necessary on the activity level. If performance value is higher than 0.85, the agent automatically moves to "solved" state. The goal is to have all product element agents in the "solved" state. However, since the agent can go back and forth from the "problem spreading" to "solved" state, several iterations might be necessary before performance stabilizes.

### 3.5. Conclusion on the developed solution

Developed software makes a step towards risk management that can consider real-life relations present during product development. The simulator captures behaviour of development process, its product and their relations. Individual risk events are added on the model to simulate external factors impacting the observed system. Hence, the output risk are the result of that overall dynamic.

The simulator uses agent-based methodology. Part of its development can be seen in Figure 4.11. Same as for the previous models, the solution is developed in Anylogic software and using Java programming language.



Figure 4.11 Development of a global risk management solution

The solution covers all previously identified relations between and within product and process. It is believed that these relations bring sufficient generality to the model, so the simulator can be applied for various development processes and their products. Risk calculation and model parameters are, on the other hand, flexible.

Functions for risk calculation, relationships impacts, iteration influence, regular and modification behaviour parameters can be easily changed to suit different user needs and to adapt to the situation onsite. For this reason, following section presents in detail user perspective of the proposed solution.

### 4. Global risk management in product development - solution utilization

Similarly as individual process and product, global risk management solution is more than a simulator. The solution also provide perspective on general risk analysis in the context of development processes. Hence, this section presents its risk assessment procedure (subsection 4.1) and its implication on decision-making (subsection 4.2).

### 4.1. Risk assessment and the proposed simulator

Global risk assessment combines the steps of individual process and product risk management solutions (Figure 4.12). Hence, detailed information regarding all process risk assessment steps can be found in Chapter 2. Product risk assessment steps can be found in Chapter 3. This section summarizes previous works and presents them in the context of global risk management. New steps dealing with process-product interaction are elaborated in more detail.

Global risk assessment starts by identifying risk. Process risk identification is based on information from risk register and their grouping into risk factors. Product risk identification is not considered since previous studies have identified risk drivers that are already included in the model. New step includes identification of process-product risk. Using the risk register data and their experience, risk analysts are searching for connections between process and the product and vice versa. While performing this step the user needs to be aware that certain process-product drivers have already been identified from the literature and implemented in the solution. These drivers include: value influence on product performance uncertainty and skill, communication, organization and vendor quality impact on technological uncertainty. If other particular connections between process and the product risk analysis.

The second step of risk assessment is risk analysis. Risk analysis deals mostly with the relations between the risk and their initial quantification. In terms of process, these steps include definition of risk network, risk event network for each risk factor and finally definition of task behaviour. The first step forms initial network between risk factors. The second step forms Bayesian network of individual risks around each risk factor and considering their appearance in different tasks in development process. Finally, in the third step of process-related risk analysis, Fuzzy Cognitive Map is defined to represent task risk behaviour. FCM is defined for each task type.



Figure 4.12 Global risk assessment process for product development

Product risk assessment is based on the decomposition of the product using FBS-linkage. This decomposition is the result of the design process. Hence, in terms of risk management it represents the network around which risk information is structured. The product risk analysis focuses on quantification of different product risks around this network. Firstly, for every product element initial risk values are set. These values will evolve during the risk simulation. Secondly, sensitivities and strengths are defined. These parameters are defined on the level of links between different product elements. They have a goal to represent probability of risk propagation from one element to the other and the influence of risk propagation between elements.

Once the individual process and product risk analysis is performed, integrated process-product analysis is conducted. This includes formulation of rules and/or conditions that define process-product interaction. As it has seen in previous section of this chapter, certain rules have been already implemented. Activity influence on the product element has been defined based on the activity type. In case any other rule exists in the real product development, it needs to be added in this phase of risk analysis.

After risk analysis is finished, the risk evaluation is performed automatically in the developed software. The software enables risk calculation and prediction and the result are focused equally on process and the product. Thus, activity overall time, cost and value is calculated. On the product level, performance risk is determined for every product element. The solution also counts number of necessary iterations on process and product level, so the process planning can be adapted based on the acquired information.

### 4.2. Implication on decision-making

The global risk management solution for product development predicts risk and can be used for scenario analysis. Hence, same as for individual product and process solutions, the main goal hasn't been to trade-off risks and make decisions automatically, but to provide adequate model that can be used in various situations.

The main strength can be summarized in two words: comprehensiveness and flexibility. Solution focuses in product and its development process with equal attention. One model is not based on the other and hence no trade-off is needed when considering mutual risks. In the same way, actors that have expertise in one of the fields can contribute to risk management. Usually, during product development designers can be asked to evaluate process risks. Since this task is out of their regular scope of work, risk management becomes time-consuming and tedious job in which they have no real confidence. With the comprehensive approach, designers can treat risk management as part of their design task. Instead of assessing global process risks, they are asked about their daily task, risks and product relations. Hence, risk management is not something incomprehensible and distant from the reality. Based on this bottom-up integration, comprehensive global risk information is provided.

Solution flexibility is based on its reutilization and extension potential. Solution defines basic elements on process and product level and their connections. On the process level solution is decomposed into different activity types. On the product level, it is made of product elements. Each basic element can hold its related information and be "plugged" into a new system with ease. Different combination of these basic elements, risk events and their factors can lead to different resulting risks. The solution can then be used as a pattern to represent different processes and products.

Another aspect of flexibility is directly related to decision-making. Having in mind that the model is developed using agent methodology, all agent-related information can be tracked in any time. Hence, on the highest agent level, new modules can be integrated to support risk trade-offs and automatic decision-making without the impact on the rest of the model.

In order to better show all the mentioned aspects of a developed approach, the solution use is illustrated with an example in the following section.

### 5. Illustrative example

After the solution has been thoroughly presented, the best way to show its use is to illustrate it in the example. In this thesis, one example has been used for all the previous chapters. In the same way, here, the risk management in hair dryer development is presented.

The example includes the first 15 tasks presented in the Chapter 2. Hence, all the process-relevant data are the same as in example in that chapter. It is considered that the goal of the tasks is to choose materials for all hair dryer components: fan, motor, heating unit, casing, power and control. Similarly as in Chapter 3, the product is considered as well known and, hence, the process-product connection are established directly on the task and structure level. For new product development, the process can be connected to the product on the functional or behavioural level. The process-product connection for the observed case is presented in Table 4.2.

Activity ID	Activity type	Product element
1	Analysis	S1, S4, S7, S13
5	Analysis	S1, S4
6	Synthesis	S1, S4
7	Choice	S1, S4
8	Analysis	<b>S</b> 7
9	Synthesis	<b>S</b> 7
10	Choice	<b>S</b> 7
11	Analysis	S13
12	Synthesis	S13
13	Choice	S13
14	Synthesis-Choice	S1, S4, S7, S13
15	Synthesis-Choice	S1, S4, S7, S13

Table 4.2 Process-product connection

As it can be seen from the table, the kick-off meeting (Activity 1) influences all product structural elements. This meeting usually has a goal to inform all the actors about the product that is to be developed. Hence, it is the place where requirements are summarized. For this reason, this and all other initial meetings are considered as analyses. They transform available data on the future product into a useful information for future design tasks. Activities 5-6-7, 8-9-10 and 11-12-13 represent a team work. The first team focuses on fan and motor design, while the second and the third team are dealing with heating unit and casing, control and power supply. The main goal of these activity triplets is to provide initial material proposition. This is performed through initial meeting, creation task and review task. As stated before, initial meeting represents analysis. Creation is a synthesis and review is a choice. After these tasks have been performed, the whole team meets for internal and external creation sessions (Activities 14 and 15, respectively). The goal of these tasks is to verify if all the individual choices form a coherent whole. Hence, these tasks are synthesis-choice and they influence all product elements. They are considered synthesis-choice since, apart from the choice of individual elements, there is an added value to form the final product. Two synthesis-choice activities are considered. The first one is performed locally, while the second includes external actor.

In order for the risk simulation to be performed, initial requirement and technology information needs to be determined. The goal of this simulation is not to choose between different technologies during simulation, but to represent overall influence on risk. Hence, if the choice between different technologies is needed, it can be performed by analysing the results of separate simulation runs. Initial requirement and technology information are presented in the Table 4.3.

ID	Description	Requirement	Technology 1	Technology 2
<b>S</b> 0	Fan geometry	1	1	1
<b>S</b> 1	Fan material	0.97	0.905	0.905
S2	Fan surface	1	1	1
<b>S</b> 3	Motor geometry	1	1	1
<b>S</b> 4	Motor material	0.96	1	1
S5	Motor control	1	1	1
<b>S</b> 6	Power supply control	1	1	1
<b>S</b> 7	Heating unit material	0.99	0.92	0.733
<b>S</b> 8	Heating unit control	1	1	1
<b>S</b> 9	Heating unit geometry	1	1	1
S10	Control system control	1	1	1
S11	Casing geometry	1	1	1
S12	Casing surface	1	1	1
S13	Casing material	0.95	0.89	0.89

Table 4.3 Technology and requirements information

Table 4.3 shows two options for technology risk and one for requirement. Different options in technology risk have a goal to simulate different choices. In this particular case, the question is: what is the influence of a less-performant heating unit material on the development process? Hence, S7 technology is firstly set to 0.92 and, later, to 0.733. Initial requirement levels are the same in all scenarios since they define the product in general. Value risk is not defined at the beginning of the simulation since it depends on process-product behaviour. Also, it is worth to notice that all requirement and technology values for all non-material structural elements are set to 1 since they are not in the focus of this simulation. In case the whole design process is simulated, these risks would also have their appropriate values.

Other process and product related information are defined in accordance with the example from chapters 2 and 3. Sensitivity between all product elements is set to 0.1. Iteration performance is 20%.

### 5.1. Obtained results S7 T= 0.92 and S7 T=0.733

Two group of experiments have been conducted. In the first one, technology risk of a heating unit has been initially set to 0.92 (S7 T=0.92). The second one tests different technology module with the initial technology risk of 0.733 (S7 T=0.733).

The results of the first study are presented in Table 4.4, 4.6 and in Figure 4.13. The second study is presented in Table 4.5, 4.7 and Figure 4.14. The first tables, in both studies (Table 4.4 and 4.5, respectively), contain activity-related information: achieved cost, time, cost of modifications, time of modifications, final value and number of iterations achieved. Comparing to the pure process-related model seen in Chapter 2, the results are now complemented with modification-related information. Hence, "modified cost" in Tables 4.4 and 4.5, represents the cost of all performed modification on the observed task. "Modified time" shows the cumulative time related to modification. Consequently,

overall time and cost values are calculated as a sum of regular cost or time risk and modified ones. The proposed solution captures other iteration-related information. Since the main criteria of process evolution is based on its achieved value, the model can track it. Hence, the final value represents the value achieved at the end of simulation when all the modification has been applied. The results also show the number of iterations each activity has passed through.

Activity ID	Cost	Time	Modified Cost	Modified Time	Final value	Number of iterations
1	81.662	29.379	98.689	3.316	1	1
5	7.489	6.707	13.329	5.376	1	1
6	19.146	24.384	4.901	22.679	1	1
7	5.489	3.284	6.514	0.704	1	1
8	7.489	6.707	6.875	5.475	1	1
9	19.146	24.384	6.526	21.119	1	1
10	5.489	3.824	3.25	0.995	1	1
11	7.489	6.707	4.295	0.899	1	1
12	19.146	24.384	21.389	3.043	1	1
13	5.489	3.824	7.184	2.117	1	1
14	66.766	19.202	85.679	5.922	1	1
15	101.823	29.245	166.087	1.262	1	1

Table 4.4 Activity - Obtained results when S7 T=0.92

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Table 4.5	Activity -	Obtained	results v	vhen	S7T=0.733
10000 1.5	11011111	obianca	results r	viicii	57 1 -0.755

Activity ID	Cost	Time	Modified Cost	Modified Time	Final value	Number of iterations
1	63.662	24.379	45.902	2.595	1	1
5	7.489	6.707	10.367	1.539	1	1
6	19.146	24.384	31.98	39.864	1	1
7	5.489	3.824	7.192	0.254	1	1
8	7.489	6.707	1.863	3.532	1	1
9	19.146	24.384	21.485	28.039	1	1
10	5.489	3.824	1.203	1.445	1	1
11	7.489	6.707	6.097	0.891	1	1
12	19.146	24.384	27.047	3.412	1	1
13	5.489	3.824	7.688	2.663	1	1
14	66.766	19.202	105.982	6.989	1	1
15	101.823	29.245	67.428	3.144	1	1

As it can be seen from the tables, on activity level, there is no difference between two scenarios. Firstly, the activities in both cases have the same behaviour. They are both using the same Fuzzy Cognitive Maps which, as it has already been shown in Chapter 2, lead to the same stable state. Hence, the cost and time risks are matching. The difference is made on the modification level since, for each performed iteration, modified cost and time are defined as a random value between 0 and the triple initial value. Final value and number of iterations are 1 for all the activities and in both scenarios. This is the direct consequence of value risk and the modification conditions.

In both scenarios, after FCM calculation the lowest possible value can be 0.9. This rule has been implemented due to fact that this design process is considered simple and not highly innovative. Hence, its performance is not seriously impacted by external risk events. Having in mind that the iteration productivity is 20%, only one iteration is necessary to obtain maximum value (V=1).

Seeming to have no issue on the process level, doesn't necessarily mean no issue in the product development. This can be observed using the product-related results in Table 4.6 and 4.7 and Figure 4.13 and 4.14. Product related results include performance values and number of iterations for all product elements. In both scenarios, it is evident that the desired performance is not always achieved. Also, the number of iterations is not necessarily limited to 1. Comparing the two scenarios, slightly better results are achieved with the higher technology value.

ID	Performance	Number of iterations	ID	Performance	Number of iterations
F0	9.03x10-5	166	B12	-	-
F1	3.754x10-5	200	B13	0.817	14
F2	7.051x10-5	181	<b>S</b> 0	-	-
F3	3.664x10-5	187	<b>S</b> 1	0.224	3
B0	0.821	5	S2	-	-
B1	-	-	<b>S</b> 3	-	-
B2	0.955	5	<b>S</b> 4	0.247	3
B3	-	-	S5	-	-
B4	0.961	3	<b>S</b> 6	-	-
B5	-	-	<b>S</b> 7	0.228	3
B6	-	-	<b>S</b> 8	-	-
B7	0.836	3	<b>S</b> 9	-	-
B8	-	-	S10	-	-
B9	-	-	S11	-	-
B10	0.828	3	S12	-	-
B11	-	-	S13	0.22	3

Table 4.6 Product - Obtained results when S7 T=0.92

In general, the worst results are achieved on functional level. Functions are connected among themselves and with the behaviours. Although sensitivity is low between the elements, highly connected nature can lead to numerous problem iterations. In case of functions, all functional elements are connected. Hence, even a small perturbation in any of the functions leads to the chain of perturbations. In this particular case, the connections between functions can lead to the infinite loop of perturbations. Hence, the iteration number is limited to 200. The activity influence can slower the functional degradation, but their influence is limited since they directly address only structure and, thus, their impact on the functions is purely implicit. Performance values are given with the high precision. However, it is better to observe these values through the threshold defining acceptable or unacceptable performance. In the case of all 4 functions, the performance is unacceptable due to the extremely low performance values. Even the 4 structural elements (S1, S4, S7, S13) suffer from the low performance.

Obtained results imply that the solution can identify the same problems types that can be seen in real product development. The designers are often obliged to focus only on their tasks and their product elements of interests. Focusing only on the particular structural element and not "seeing the bigger picture" can lead to the problems that have been identified in this example - the main product functions might not be achieved. Tasks should directly address all element types. However, behaviours and functions often depend on the factors that are not under direct control of the observed designer. Hence, this tool can help in connection calculation and visualization.

ID	Performance	Number of iterations	ID	Performance	Number of iterations
F0	7.529x10-6	200	B12	-	-
F1	1.002x10-5	199	B13	0.749	14
F2	5.268x10-6	194	<b>S</b> 0	-	-
F3	2.259x10-5	200	<b>S</b> 1	0.224	3
<b>B</b> 0	0.895	2	<b>S</b> 2	-	-
B1	-	-	<b>S</b> 3	-	-
B2	0.797	11	<b>S</b> 4	0.247	3
B3	-	-	<b>S</b> 5	-	-
B4	0.996	1	<b>S</b> 6	-	-
B5	-	-	<b>S</b> 7	0.181	3
B6	-	-	<b>S</b> 8	-	-
B7	0.836	3	<b>S</b> 9	-	-
B8	-	-	S10	-	-
B9	-	-	S11	-	-
B10	0.807	3	S12	-	-
B11	-	-	S13	0.22	3





Figure 4.13 Product elements performnce - S7 T=0.92

Figures 4.13 and 4.14 illustrate product performance. Here, the product elements not impacted by the design are shown in green. Elements in red indicate performance value lower than 0.85, while yellow elements show the elements with the satisfactory performance (higher than 0.85 in this case). Hence, using the proposed solution, user can visualise influence between different elements. Having in mind that each element is defined by activities, the task impact on product performance can be indirectly

tracked as well. This can help development team to identify places for needed improvements on both, process and product levels.



Figure 4.14 Product elements performance - S7 T=0.733

### 5.2. Obtained results S7 T= 0.92 and S7 T=0.733 with modified modification condition

After the initial simulation has shown certain problems traight appear in the product development, modification of the model conditions has been made to illustrate the changes that they may have on the system as a whole.

Focusing only on activity value is just one step towards product performance management. Product performance risk depends also on its technology uncertainty which is in direct relation with certain task factors: worker/designer skill, vendor quality, organization and overall communication. However, those aspect are not considered too relevant when comes to product development.

This is the time to bring back the case of Airbus A380 where organizational and communication issues lead to the enormous product and project problems. The question is: Can the proposed model illustrate the inclusion of the mentioned factors and their effect on general risk in development?

Organization, communication, skill and vendor quality are already part of FCM map and activity behaviour. They are included in the calculation of product technology uncertainty. However, in the previous model they are not considered as a modification criterion during task iterations. In other words, they evolve as long as activity value evolves. Their values are improved using iteration productivity whenever new iteration is executed, but they haven't been considered relevant to initiate new iteration. In this example, new iteration is initialized if value and technology factors are below 0.95. This criterion

is implemented only for activities that have impact on product technology uncertainty – synthesis and synthesis-choice.

The improvements are evident even through simple visualization, shown in figures 4.15 and 4.16.



Figure 4.15 Product elements performance - S7 T=0.92 and technology modification criteria included



Figure 4.16 Product elements performance - S7 T=0.733 and technology modification criteria included

As it can be seen in the figures, product performance is strongly improved. In the scenario where technology is more performant (T=0.92), the product performance is satisfactory for all elements. In the second case (T=0.733), unsatisfactory performance remains only on functional level. Hence, monitoring technology factors on activity level can have a positive effect on the product under development.

Numerical results in Tables 4.8 - 4.11 illustrate changes on the activity and on the product level. Contrary to the previous model, number of iterations on activity levels is not 1. For the activities considering technology factors, it is necessary 7 or 8 iterations to reach satisfactory levels. This leads to the increased modification cost and time for those activities. However, this model can provide more realistic prediction of a number of necessary iterations during product development.

Activity ID	Cost	Time	Modified Cost	Modified Time	Final value	Number of iterations
1	24.379	63.662	14.1	12.58	1	1
5	7.489	6.707	9.677	3.983	1	1
6	19.146	24.384	139.847	156.794	1	7
7	5.489	3.824	6.076	2.237	1	1
8	7.489	6.707	13.543	1.377	1	1
9	19.146	24.384	144.685	182.836	1	7
10	5.489	3.824	4.79	0.705	1	1
11	7.489	6.707	2.192	0.053	1	1
12	19.146	24.384	134.89	153.53	1	7
13	5.489	3.824	7.588	2.796	1	1
14	66.766	19.202	551.338	86.288	1	8
15	101.823	29.145	687.182	51.717	1	7

Table 4.8 Activity - Obtained results when S7 T=0.92 and technology criteria included

Table 4.9 Activity - Obtained results when S7 T=0.733 and technology criteria included

Activity ID	Cost	Time	Modified Cost	Modified Time	Final value	Number of iterations
1	63.662	44.379	108.941	1.043	1	1
5	7.489	6.707	7.433	0.87	1	1
6	19.146	24.384	97.793	86.958	1	7
7	5.489	3.824	4.687	0.251	1	1
8	7.489	6.707	0.044	4.285	1	1
9	19.146	24.384	139.267	101.15	1	7
10	5.489	3.824	3.091	2.925	1	1
11	7.489	6.707	1.335	0.728	1	1
12	19.146	24.384	130.525	109.499	1	7
13	5.489	3.824	6.472	2.638	1	1
14	66.766	19.202	536.609	53.978	1	8
15	101.823	29.245	709.819	63.217	1	7

On the product levels, number of iterations has been decreased and better performance has been achieved. In T=0.92 scenario, there is no problem even on a functional level. In the second scenario, the functions enter their loop as in previous cases. This can imply that a regulation of process influence can be one part of the solution. The second part might be functional decomposition to avoid many to many relations between product elements.

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ID	Performance	Number of iterations	ID	Performance	Number of iterations
F0	1	1	B12	-	-
F1	1	1	B13	1	13
F2	1	1	<b>S</b> 0	-	-
F3	-	-	<b>S</b> 1	1	3
B0	-	-	<b>S</b> 2	-	-
B1	-	-	<b>S</b> 3	-	-
B2	1	10	<b>S</b> 4	1	3
B3	-	-	<b>S</b> 5	-	-
B4	-	-	<b>S</b> 6	-	-
B5	-	-	<b>S</b> 7	1	3
B6	-	-	<b>S</b> 8	-	-
B7	1	3	<b>S</b> 9	-	-
B8	-	-	S10	-	-
B9	-	-	S11	-	-
B10	1	3	S12	-	-
B11	-	-	S13	1	3

Table 4.10 Product - Obtained results when S7 T=0.92 and technology criteria included

Table 4.11 Product - Obtained results when S7 T=0.733 and technology criteria included

ID	Performance	Number of iterations	ID	Performance	Number of iterations
F0	1.505x10-5	187	B12	-	-
F1	1.126x10-5	191	B13	1	7
F2	6.747x10-6	200	<b>S</b> 0	-	-
F3	2.649x10-5	176	<b>S</b> 1	1	3
B0	1	3	<b>S</b> 2	-	-
B1	-	-	<b>S</b> 3	-	-
B2	1	4	S4	1	3
B3	-	-	S5	-	-
B4	1	2	<b>S</b> 6	-	-
B5	-	-	<b>S</b> 7	1	3
B6	-	-	<b>S</b> 8	-	-
B7	1	3	<b>S</b> 9	-	-
B8	-	-	S10	-	-
B9	-	-	S11	-	-
B10	0.991	3	S12	-	-
B11	-	-	S13	1	3

To conclude, it can be said that the proposed solution can illustrate and calculate interactions that exist between a process and a product during development. The solution defines general relations that can be easily adapted to suit the needs of a user. This has been shown through the second example in this section. The future work can then focus on identification of other rules and their implementation in the current model.
## 6. Conclusion

Chapter 4 presents a comprehensive solution for process-product risk management. The main goal of this new approach has been to identify and implement certain interactions that exist within a process and a product, but also between the two. This will, hopefully, lead to the future practice in risk management. In general, the solution contributions can be summarized in the following manner:

- It provides comprehensive process-product view on the risk management.
- It enables bottom-up quantifications of risk interactions.
- It supports qualitative and quantitative rule determining which can be used in different development phases and based on different data sources.
- It is flexible to the addition of new rules and relations.
- It enables risk management that follows the main development processes and their products.

The solution aims at quantifying risks while answering some of the common questions that may appear during product development. What is the influence of a chosen technology? Is the current iteration strategy leading to satisfactory product performance? How worker's experience impacts the development? The solution is based on the adapted links from the literature, but it can be extended or detailed with new ones. Hence, it can be used as a base for risk management that can be modified to suit particular needs.

This and other aspect of the proposed solutions are discussed in Chapter 5.

# Chapter 5: Discussion and conclusion

#### Abstract

This chapter shows the main contributions, limitations and prospects of the thesis. The conclusion summarizes all the results based on the scientific issues and identified needs in the practice. Limitations include applicability of the solution on different development processes, information collection and solution adoption by the users. For all identified limitations, the solution has been proposed. Thesis is observed as a development process to show the broadness of the approach. Survey has been proposed to collect information and model the development process. Serious game has been applied to introduce main ideas to the user and to ease the adoption of the solution. The chapter is finished with the perspectives.

The thesis work has been performed to explicitly **consider process and product risk interactions** and to develop **global solution**. The environment in which the solution is made has been mostly academic. Studying various approaches and frameworks has offered broadness to the solution and verification on the literature-inspired example. Different perspectives of the same example have been shown through the three chapters (Chapter 2, 3 and 4). While this example and the observation made at the end of each chapter show the main results, in this chapter global conclusion and discussions are presented. The first section focuses on the general conclusion. It summarizes obtained results based on the identified scientific issues (Chapter 1) on one hand and practical observations from the other. In the second section, certain limitation that the current solution may face are presented and the corresponding activities performed to overcome them. Lastly, perspectives are underlined.

#### 1. General conclusion

Developed global risk management solution for product development is compared with the scientific questions from the beginning of the thesis (Chapter 1) and from the perspective of risk management demands seen in practice.

#### 1.1. Conclusions on obtained results comparing to the scientific questions

The main goal of the thesis has been to propose global risk management solution for product development processes. The main scientific issues of the thesis can be summarized in Figure 5.1.



Figure 5.1 Global risk management scientific issues

The first requirement has been to provide adequate product representation to enable modelling of risk behaviour. The second scientific question has focused on the same problems in the development process: process representation and modelling of risk behaviour. In both cases, the goal has been to include risk interactions and to enable propagation of risk through process / product. The third requirement merges process and product into a whole. Hence, the main goal has been to model process-product interactions and risk propagation. The fourth and the fifth requirements are determining the general aspect of the thesis. The solution should support risk management process with the special focus on risk assessment and risk evaluation. Additionally, the approach must support decision-making by providing adequate quantitative evaluation for different scenarios and actors. In that sense, the solution should possess adequate dynamic and tailoring possibilities. With previously mentioned in mind, thesis contributions can be divided into three axes: process-, product- and process-product related.

Process-related risk management is a comprehensive solution covering all aspects from framework to simulator. The developed solution is based on the separation between the external events and internal behaviour. This is important since it makes the clear distinctions between the controllable and uncontrollable aspect of risks. Most of the conventional risk management methods are treating the two together, leading to the vague possibilities for the management. Also, this type of separation enables both statistical and systemic view of risks. Hence, the solutions can be used in its simpler form without the extensive data or in the advanced form in conjunction with risk database. Since the risk behaviour is modelled on the task level, the solution provides bottom-up integration of risk. The integration and propagation are based on the process flow. This manner of defining risk alters from the standardized approaches which are usually based on the global risk knowledge. Hence, they require great expertise or the appropriate data. With the approach proposed in this thesis, each actor is considered expert in its own work. Hence it participates in the definitions of risk behaviour for the field where he or she is in charge. While all the aspect (identification, analysis and evaluation) of risk assessment are directly present, the risk becomes closer to the user. It is the process flow that takes it to its general form and not the other way around. After the initial effort, the solution can be reused. It can be considered as a behavioural pattern for different development processes. Thus, the solution separates the "unknown" from the "ourselves", but also defines interaction and propagation of risk as requested at the beginning of the work. This representation of risk so far hasn't been identified in the literature. Lastly, the result of the overall flexibility of the solution is summarized through multi-path and multi-view risk analysis.

The product-related risk management solution provides a comprehensive overview on the product performance risk. It considers different risk sources including technology, requirement and those related to the performance quality of the underlying development process. The propagation is based on the connections and sensitivities between the product elements. Since each individual path is determined randomly, the solution can be used for the identification of risk by analysing different propagation paths. This can be a step towards automated identification of risk which is currently not covered in the appropriate standards. The solution is also capable to take into account iterations and solutions, which is scarcely identified in the literature. Hence, the risk of the development process can be observed from the product point of view. All risk interactions and propagations are directly represented. Similarly as in the process-related solutions, the simulation the solution can become a powerful tool for decision-makers enabling them to assess the critical component, compare different design solutions, calculate recurrences and iterations, or average risk on the product level.

The global process-product risk management solution combines the functionalities of the two individual solutions. Additionally, it explicitly models iterations and their effect on product and the process. In that sense, every activity can be modified due to the unsatisfactory product performance or due to the higher risk on the activity level. Also, product can be improved based on the activity limit. In that sense,

the solution once again tries to capture behaviours present in the real development. The risk becomes more integrated with the development process and the product. The solution can be used to evaluate different product or process modules and their influence on the overall development risk. Subjective (actors' views) risk can be combined with the objective risk information (obtained for example through statistical analysis of different events). In that sense, the results can be used to compare different perspectives on the risk affecting the common process and the product. Considering that the evaluation of different scenarios can be performed almost instantly using the developed tool, the solution could be used to ease the understanding between development teams. In other word, the solution possesses sufficient flexibility to answer to different "what if" questions in a highly dynamic product development environment.

The proposed solutions have achieved the main requirements set at the beginning of the thesis. However, it is necessary to analyse how this solution suits the needs in the risk management community. The next subsection focuses on this aspect of the solution.

#### 1.2. Conclusions on risk management practice and obtained solution

"Give me six hours to chop down a tree and I will spend the first four sharpening the axe."

Abraham Lincoln

Cooper (2003) in her practitioner perspective on the need for new risk management solution underlines the following characteristics as necessary:

- 1. Enabling users to work at multiple levels of abstraction
  - scanning the environment to become aware of possible ideas;
  - conducting brief evaluations of ideas to determine if the idea is worth pursuing;
  - conducting in-depth analysis of ideas.
- 2. Provide multi-path connectivity and multi-criteria control for information access
- 3. Determine what type of information would be relevant;
- 4. Determine when it would be most relevant;
- 5. Be able to effectively match existing information to the target user.

The developed solution has been made with the idea to cover all or majority of mentioned requirements. Thus, the solution enables multiple levels of abstraction on process and product levels. Granulation on activities of different level can suit the risk simulation according to the current needs. On the other hand, product decomposition considers all product levels from components to systems. As required, the solution also enables multi-path risk analysis. For this reason, Monte Carlo simulation can be conducted to enable global view on process-product risks. Also, individual paths can be studied for risk identification. Regarding the information relevance, it can be said that the solution is based on different literature studies. Hence, certain behaviours are predefined to guide users in their personal risk assessment. Individual risks, drivers and factors are clearly separated in process and product levels. The user actively creates its own process (FCM) and product (FBS) behaviour and hence can adapt the information if necessary. Timing is based on the process plan and the information available. Consequently, risk management follows the logic of a development process. Lastly, developed risk simulator support different behaviours to be simultaneously evaluated. In that sense, different stakeholders and their risk views can be considered.

On the other hand, Schindel (2010) on existing risk management solutions (FMEA) emphasizes the following:

- 1. Too labour intensive to encourage engagement
- 2. Somewhat arbitrary in identifying issues
- 3. Overly sensitive to the skills and background of the performing team
- 4. Not building enough confidence of fully identifying the risks of systems failure.

While majority of these observations (bullet points 2, 3 and 4) have already been elaborated in the thesis, it is interesting to discuss the first remark. FMEA is the type of approach that can be summarized through the identification of scenarios (failure modes) and their effects. In that sense, it is one of the least labour intense approaches in risk management. Other approaches (Bayesian, FTA) including the developed one require more effort to enable initial risk assessment. In the thesis case, after the first model is built with the correct information, the solution can be reused for different development processes. Hence, the amount of work decreases through reutilization, but nevertheless initial effort can still be greater than the one needed to build FMEA. Expecting miraculous risk management solutions without engagement is not possible at this moment.

While data-driven solutions will surely be the future of risk management, in order to profit from their results, the data need to be gathered and the model needs to be built. In the thesis, the needed information based on different literature resources is emphasized and the model is developed around them. Still, to enable effortless risk assessment form user perspective the data need to be collected. If availability is considered as important factor impacting development risk, user should provide adequate availability information of the team involved in development process. Similarly, if skill is considered relevant, skill-related database need to exist. If not, the user needs to provide this information in the form of expert opinion. Hence, if data are not collected, effort needs to be made.

It is evident, however, that the data for the new solutions don't exist at the moment of their creation. For this reason, risk simulator presented in this thesis can be driven using, both, expert opinions and database information. This flexibility is considered important for one more reason. Analysing a system through expertise and data provides complementary views on the problem. By analysing the behaviour of a system, knowledge can be deepened which can lead to better project management. Also, certain experts can recognize behavioural patterns that are not visible in the current data collection. On the other hand, data can remove potential biases in opinions.

To conclude, risk management is a process as any other and, yes, it requires effort to perform it. The main question in risk management is not if we can do it without any engagement. Because we don't ask if we can develop a product by doing nothing, don't we? The question is how to perform risk management to get the most comprehensive result with the invested effort.

The developed solution provides comprehensive bottom-up process-product view on risk. It can help the users to get to know their systems and to see how individual events impact them. However, it requires an effort in the same way as sharpening the axe before woodcutting. But the sharper the axe is, the easier is to cut down a tree.

However, it would be unrealistic to say that the current solution doesn't have any limitations that can't be improved. It is believed that those limitations are mainly oriented toward suitability of the solution for different development problems, gathering of relevant information and model adoption from the user perspective. Consequently, the following sections focuses on these aspects and proposed appropriate analysis and solution.

## 2. Solution limitations and how to respond

Three potential limitation related to the developed risk management solution have been identified:

- Applicability of the solution on different development processes,
- Gathering of relevant information necessary for risk modelling,
- Adoption of the solution by the user.

Proposed solutions have been illustrated on the development of a common home appliance (hair dryer). While this example can be easily mapped on different engineering domains, the question is whether it can be suitable for product in a large sense of this term. Section 2.1 aims at answering this question and exploring the limits of the proposed solution in the sense of its applicability on different development processes. Apart from this potential problem, it might be said that the risk management solution uses various concepts and terms that might be overwhelming for the users and that can make it hard for them to build the risk model. For this reason, Section 2.2 focuses on the means for information gathering and model building. As a complementary answer to the mentioned issue, Section 2.2 shows how to bring solution closer to the user and to ease its adoption.

### 2.1. On solution applicability to different development processes

The utilization of a proposed solution has already been presented. In this section, the new example, from another area is used to show general applicability. The model is built from scratch. Thus, this example indirectly shows one possible manner of model building. In that sense, it also partially covers second limitation.

The term "product" can gather various solutions from mechanical to software engineering. Proposed risk management solution has already been illustrated on this type of products. On the other hand, thesis can be considered as a development process where the main "product" is the solution to the scientific question. In that sense, the solution developed in this thesis can be applied to consider main thesis risks. Consequently, it can represent general applicability of the risk management solution.

Additionally, representation of thesis risk can be used to develop risk models for another thesis. Also, this example can show how an actor involved in the work can contribute to the risk model. In other words, how hands-on knowledge can be implemented into a risk management solution.

#### 2.1.1.On solution applicability - process aspect

Globally speaking in order to produce a solution to the scientific question at least three activities need to be performed: analysis, synthesis and choice. Analysis includes problem introduction and literature analysis. Synthesis creates the solution based on the requirements, previously gathered information and knowledge. Finally, choice is made between different options. If possible, choice is supported by evaluation that compares the gap between the desired and achieved outcomes. In this thesis, these three activities have been performed for all main scientific questions: process risks, product risks and process-product risks in the development.

The thesis can be modelled like a process behaviour. Hence, FCM needs to be made. In order to define and use FCM, Jetter & Kok (2014) suggest to follow several steps:

- 1. Classification of objectives and information,
- 2. Plans for knowledge elicitation,
- 3. Knowledge capture,

- 4. Calibration and detailed FCM design and
- 5. Model use and interpretation.

The main objective for the thesis model is the same as product development model – represent output development risks. These risks include time and value. Cost is not explicitly considered in the thesis. However, in product development it would be inevitably present. Regarding the knowledge elicitation, Jetter & Kok (2014) propose three methods: modeler is an expert, modeler surveys the expert(s) and modeler analyses documents. For the thesis model, the first and the third approaches have been applied. Other steps are explained in the rest of this section.

General task behaviour for all the mentioned activity types is represented in Figure 5.2. This behaviour is the author's interpretation of risk factors and their relationship that impact the thesis work. Author considers that all the activity types depend on the mentioned factors. However, the impacts between them may vary. For example, input information in the synthesis task can highly influence value risk. However, input information in analysis task is usually intentionally broad. This uncertainty has a weak influence on the analysis value. Similar discussions and observations can be applied on other risk factors and activity types. The behavioural model shown in Figure 5.2 represent global risk behaviour illustrated as FCM. The link values can differ for different activity types.



Figure 5.2 General task risk behaviour model

The circles in Figure 5.2 represent different risk factors that impact the thesis. They are selected based on author's opinion and general FCM presented in Chapter 2. Output risks include time and value. Time represent schedule problem, while value represent quality of the performed work. All risk factors represent problems. As an example, "skill" means knowledge issue. The connectors represent influences between factors. Their weights can be illustrated using the linguistic variables: positive weak (PW), positive medium (PM), positive strong (PS), negative weak (NW), negative medium (NM) and negative string (NS). For each linguistic variable, exact value or membership function can be assigned.

Representing linguistic variables using membership functions implies that the actual weight is determined in a same manner as in fuzzy logic. In both cases, the weight values are mapped between [-1, 1].

The weights have been determined based on the personal experience. Hence, to make a general FCM on PhD process it is necessary to survey different PhD candidates willing to represent their experience in a map. This manner of knowledge representation would be, as well, applied for development processes. Different actors could be interviewed to illustrate their experience. Their maps can then be merged into one or they can remain separated to illustrate different point of view on risks. It is important to notice, however, that even this map illustrates how broad the application of the developed solution can be.

Once the initial map is developed, it is necessary to calibrate risk behaviour. In other words, to test it and to see if it gives the results according to experience. To perform this, several events that happened during the thesis and their impact have been considered: administrative issues, COVID-19 and communication problems. The thesis is planned to be performed as a double degree program between two schools in France and in Canada. Canadian administrative issues prevent this from happing. This issue also had impact on other aspect of the thesis since it has been initially planned to collaborate with industrial partner in Canada. Similarly, small communication problems due to the intercontinental communication lead to different view on the scientific questions between the two teams involved. Apart from this, during the thesis it has been planned to spend a semester in Germany and potentially work on industrial case. However, COVID-19 delayed these plans.

The first two issues have been present at the same time. Their influence has been mostly on schedule. The thesis planning has been highly unstable. Productivity has also been endangered due to the constant problems and miscommunication. This all lead to the solution that is closer to the view and ideas supported by the French team since the communication with this team has been strong, straightforward and constant. The presented model is used to simulate the effect of the following events. The two events have impacted organization and communication. Hence, the values of risk factors are greater than zero. Organizational factor has been set to 0.7 indicating quite a big issue in this area. The communication problem is considered minor and hence the factor value is set to 0.3. All other initial risk factor values are set to 0. Initial vector and FCM matrix are shown in Figure 5.3.

	ΓO	0.75	0	0.5	0	0	0	0	0	0	ך 0	ſ
	0	0	0	0.25	0	0	0	0.25	0	0.5	0	
	0	0.5	0	0	0	0	0	0	0	0	0.5	
	0	0.75	0	0	0	0	0	0	0	0	0.75	
	0	0.25	0	0	0	0	0	0	0	0	0.25	
FCM =	0	0.75	0	0	0	0	0	0	0	0	0.5	
	0	0.25	0	0	0	0	0	0	0	0	0.25	
	0	0.25	0	0	0	0	0	0	0	0	0.5	
	0	0.25	0	0	0	0	0	0	0	0	0.5	
	0.25	0.5	0	0.25	0	0	0	0	0	0	0.75	
	L 0	0	0	0	0	0	0	0	0	0.75	0 ]	

Figure 5.3 Input vector and FCM for the thesis model

The obtained output vector is:

*OutputVector* = [0.72 0.99 0.659 0.842 0.659 0.659 0.659 0.726 0.659 0.893 0.981]

The result indicate that the highest risks are visible on performance, value, schedule and motivation. This corresponds to the personal impression of risk throughout this thesis. The administrative and communication issue have highly impacted productivity. During the first two years, the work has been constantly divided between administration and research. Hence, additional effort was necessary to overcome these problems and to provide results that were endangered as well. Value risk during the thesis has been to provide inadequate solution and to not have an industrial partner. While the first risk has been avoided, the second one has been materialized since Canadian industrial partner did not take part due to the administration problems. Hence, it is considered that the high value risk obtained during simulation is also adequate.

On the other hand, it is questionable whether the obtained results are too sensitive to initial risks. While the ranking between the obtained severities is considered adequate, the actual value might be too high. Hence, the weights can be subject to scaling.

It is also interesting to discuss impact of COVID-19. This risk event is classified as an organizational issue with a severity of 0.6. The FCM model is the same and hence all the weights between the risk factors. The obtained output vector is the same as the vector obtained in the previous case. This means that the two scenarios lead to the same stable state of the system. While, again, the ranking of risk severities can be considered adequate, the severities in the second scenario are considered too high.

This can be explained in two ways. The first and the second scenario are similar (both have medium to high organizational issue). However, the second scenario has appeared in the mature phase of the thesis where significant knowledge has been already gathered due to previous organizational issues. Hence, the two perturbations can indeed have the same effect magnitude. In that case, it is just a personal impression that those two events do not lead to the same severity. This can be confirmed or contested by comparing different points of view. In the case of the thesis model, this would require surveying other PhD candidates.

If contrary to expectations, the two scenarios have the same final state, the model needs to be adapted. This modification may include different normalization boundaries when translating obtained value into real risks or changes can be made on FCM matrix. The changes can be in form of weight modification or rule based FCM can be developed to make a clear distinction between different scenarios. If the second option is chosen, the reason for creating specific rules need to be sufficiently general to support this decision.

Additional model precision asks for additional effort. This effort can be in form of data gathering (surveys, but also exact data collected systematically) and in form of additional rules reflecting the data. It is on problem expert to decide if these changes are necessary or not. In any case, the solution proposed in this thesis can be used throughout the process since it can be used independently or with a database. Also, as seen through the example presented in this chapter and in the ones presented in other chapters, the solution is capable to capture risk relations in development processes in general.

#### 2.1.2.On solution applicability - product aspect

In the same way as with development processes, it is believed that the solution can consider "products" in the broad sense of the words. Obviously, the solution has been based on the engineering solutions that are characterized with the appropriate structure. However, the same decomposition can be applied

on the scientific question and, consequently, simulator developed in the thesis. The FBS decomposition of a scientific issue and its solution is, thus, presented in Figure 5.4. The first part of the figure (Figure 5.4a) decomposes scientific issue in a general manner. This is the type of decomposition that could have been used at the beginning of the solution development. In this stage, it can be said that the main structural building blocks are process elements, process risks, product elements and product risks. The process elements and its risks form process behaviour. Product elements and their risks form product behaviour. Although the two behaviours are built independently, they interact on the behavioural level. It is this connection that forms process-product interaction. This connection indirectly impacts the main functions of the thesis solutions – calculation of process and product risks that are formed from individual behaviours.



Figure 5.4 Scientific question decomposed using FBS linkage: a) initial decomposition; b) final solution

Later phases of solution development lead to more precise solution decomposition (Figure 5.4b). Here, process structure includes activities and their identified risk factors. The process behaviour includes Fuzzy Cognitive Maps that are made of risk factors and their relations. Activities and their link enable the precedence relationships in the product development. On the product side, the main structural elements are product elements (functions, behaviours and structures) and product risk factors

(technology and requirement). Links between product elements enable representation of reciprocal relations. Product risk factors form product performance (product risk interactions). Product performance depends on process risk and vice versa. This connection represents process-product interaction.

In the final form, FBS decomposition of a proposed solutions includes agents and risk factors on structural level, statecharts and functions on behavioural level and the functions and conditions forming final output risks on a functional level.

To conclude, the approach can be used for various development processes. On the product level and on the process level, the solution can represent risk interactions and evaluate various risks of interests. Detailed user guide for developed software can be found in Appendix C. Users can use it as a guidance to perform their own risk evaluation in the simulator. This way, risk management is to evolve as the process and product evolve.

### 2.2. On gathering of relevant information for risk modelling

Previous section has shown how the developed approach can be applied to gather information when a modeler is also a process expert. However, in majority of cases the solution would be applied by users who are not necessarily familiar modelling. The focus on this section is on gathering information for process risk model since it is believed that product model requires information that designers and other actors are well familiar. Hence, in this section shows how to survey the experts to guide them in FCM creation.

The test survey has been created and tested on a small group of respondents. The main goals of these activity can be summarized as follows:

- To test the general process information collected from the literature and see how this model will evolve to suit different users.
- Identify a proper manner to collect the information necessary for process modelling.

The exact copy of the conducted study can be found in Appendix D. The survey has been posted on Google Forms and Microsoft Forms. A small group has been asked to fill in the study: 2 experts from the academia and 3 from the industry (2 mechanical design engineers and 1 project manager in information technology). Their results are presented in the rest of this section.

2.2.1.Result obtained from the test survey – process model elements and their relations

The results presented in this section are dedicated to the model information. One of the goals of the developed process model has been to provide sufficient generality for customized modelling that is to be performed by the user. For this reason, FCM presented in Chapter 2 contains parameters that have been identified and considered relevant in the literature. Hence, the first question in the survey has been dedicated to the risk factors. The respondents were asked to assign the parameter to the activity type if they think it's relevant for the risk calculation. They also had a possibility to add and define risk factors that were not initially suggested for them. Risk factors and their activities are presented in Table 5.1. The responses obtained are divided into "academics" (see "A" in Table 5.1) and "industry" (see "I" in Table 5.1). Due to the small sample size, the results are not presented as percentage but rather as number of responses considering the group size. This way it is emphasized that the results are representing only the opinion generated on a small sample size. Further surveys are necessary to obtain results that can be used in general purposes.

Parameter	Inclu Ana	ded in lysis	Inclue Synt	ded in hesis	Inclue Che	led in bice	Included in Evaluation		
	Α	Ι	Α	Ι	Α	Ι	Α	Ι	
Availability	2/2	2/3	2/2	2/3	2/2	3/3	2/2	2/3	
Performance	2/2	1/3	2/2	3/3	2/2	0/3	2/2	2/3	
Skill	2/2	3/3	2/2	1/3	2/2	2/3	2/2	2/3	
Motivation	2/2	2/3	2/2	2/3	2/2	3/3	2/2	1/3	
Equipment availability	2/2	3/3	2/2	3/3	2/2	2/3	2/2	1/3	
Equipment support	2/2	2/3	2/2	1/3	2/2	0/3	2/2	2/3	
Vendor quality	2/2	2/3	2/2	3/3	2/2	2/3	2/2	2/3	
Vendor reliability	2/2	3/3	2/2	3/3	2/2	2/3	2/2	0/3	
Input	2/2	3/3	2/2	2/3	2/2	2/3	2/2	1/3	
Control	2/2	1/3	2/2	1/3	2/2	2/3	2/2	2/3	
Method	2/2	3/3	2/2	2/3	2/2	2/3	2/2	2/3	
Project dependency	2/2	3/3	2/2	3/3	2/2	3/3	2/2	0/3	
Project importance	2/2	3/3	2/2	3/3	2/2	2/3	2/2	1/3	
Organization	2/2	2/3	2/2	3/3	2/2	1/3	2/2	3/3	
Communication	2/2	2/3	2/2	2/3	2/2	2/3	2/2	3/3	

Table 5.1 Risk factor and their activity types. A represents the answers from the academics and I from the industry.

As it can be seen from the table, the list of risk factors formed in this thesis based on the literature and Kendrick's (2003) risk register can be considered sufficiently broad. Only one comment has been made on a possible inclusion of vendor availability as a separate parameter. This information is normally included in the "vendor reliability" since the mentioned represents the probability that the work assigned to the vendor will be performed on time. Here, vendor availability is considered implicitly and included with other factors that may lead to the reliability issue. The main reason why this factor is not considered separately is the distinction between external and internal actors. While all relevant information considering internal actors are always available to the project staff (worker's availability, performance, skill or motivation), the same can't be said for external actors. External actors don't directly belong to the development team and hence certain limits in information availability are made to represent this constraint. In case that external actors are directly and transparently present in the development process, they can be modelled as internal actors with their risk factors (availability, skill, performance, motivation).

Observing all risk factors, distinctions between the areas can be seen. Academics considers that all identified risk factors should be used throughout different activity types. Industry respondents, however, do not consider that all parameters are important for all the activities. This clearly distinguishes different views on the risk. While the survey is small and its results can't be considered as a rule, it is clear that the solution can be used to represent different views on the risk that can surely be present between users. The potential reasons for different points of view present in the conducted survey are discussed in section 2.2.2.

Another model parameter has also been investigated in the survey. In the default model configuration, in case that multiple actors, equipment, vendors, inputs, controls or methods are used in the same activity, their mean values are used to define current risk factors value. Hence, series of question are dedicated to identification of representations that can be used to describe individual impact on a group. The results are presented in Tables 5.2 - 5.5.

Donomotor	Μ	in	Μ	ax	Mean		
Farameter	Α	Ι	Α	I	Α	Ι	
Availability			1/2	2/3	1/2		
Performance		1/3		1/3	2/2	1/3	
Skill		1/3	1/2	1/3	1/2	1/3	
Motivation					1/2	2/3	

Table 5.2 Influence of a group of individual actors on their risk factors

Deverator	M	lin	Μ	ax	Mean								
Farameter	Α	I	Α	Ι	Α	I							
Equipment availability			2/2			2/3							
Equipment support	1/2	1/3		1/3	1/2								
Paramatar	Table 5.4 Influence of a group of vendors on their risk factors   Min Max   Mean												
I al ameter	Α	Ι	Α	Ι	Α	Ι							
Vendor reliability					2/2	2/3							
Vendor quality				1/3	2/2	1/3							

#### Table 5.3 Influence of a group on equipment risk factors

Table 5.5 Influence of a group of inputs, controls or methods on their risk factors

Do no ny ofori	Μ	in	М	ax	Mean		
Parameter	Α	I	Α	I	Α	I	
Input (quality)			1/2	2/3	1/2	1/3	
Control (quality)			1/2	1/3	1/2	2/3	
Method (quality)			1/2		1/2	3/3	

As it can be seen, the respondents have identified different representations for different risk parameters. This information can be used to adapt the model to the user's needs. Having in mind that the current model already considers mean value, these adaptations can be easily implemented. However, certain respondents have made comments on the calculation that would require additional work from, both, a user and a modeler. Firstly, one comment indicated that it would be beneficial to use Gantt charts to show availability of actors and equipment. In order to implement this suggestion, Gantt charts need to be digitalized and connected to the database. The changes in the model is not necessary unless each individual actor or equipment needs to be separately included in FCM. If the user prefers this option, he or she should work with a modeler to define appropriate risk behaviour. Second comment has been made on representation of motivation and skill. The respondent suggested to use case study to determine how lack of motivation or skill impacts the team. Lastly, another respondent expressed the willing to study separately every vendor. Implementation on all the mentioned is possible. The proposed solution can cover various rules and models that can be potentially identified. However, these comments mostly depend on the user willing to conduct the study and provide the data.

The survey also demanded if different calculations are to be applied based on activity type. One answer from academic and one from the industry are supporting different calculation. Respondent from the industry provided a list of potential calculations based on activity type and risk factors. Other respondent suggested to use big data analysis to determine appropriate calculation. This idea has already been discussed several times in the thesis. The main problem that can be seen in risk management for development processes is the lack of information. Hence, if there is no appropriate data, the behavioural laws need to be determined based on the expertise like the one seen in this survey.

Last question had a goal to determine if previous inputs or controls should be separated from inputs and controls. One respondent considers that they should be observed separately, while others consider they do not. The justification for separation lies in the fact that the two are created separately and consequently their influence may be different. This respondent also suggests that each input should be tested as a separated scenario. The developed solution supports both options. Also, separate testing of parameters is possible through "what if" analysis.

After all the questions have been answered, the industrial respondents have been asked to build their own FCM for every activity type. These maps are shown in Figures 5.5 and 5.6.

Input	Vector	= [A]	Р	S M	t R	Q	E	lqA	Ε	qS	Ма	ic	F	С	I	PI	Imp	D C	от	0 Т	Cost	V]
	ΓO		W	w	0	0	0	0	0	0	0	0	0	0	0	0	0	0	M,	, VS, 1	M, 0.5	0 1
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	S	, <b>S, 1</b>	0	0.75
	0.5	s VS,	0.75	0	W	0	0	0	0	0	0	0	0	0	0	0	0	0		0	S	<i>S, VS</i>
	0	М,	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	VS
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Μ	,0.25	М	S
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	<i>S</i> , 0.5
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<i>S</i> , I	W, 0.5	0.25	0
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5,	0.25	W	0
	0	0	.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	VS	S,Yes	0	VS
FCM_Analysis		N	1,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		J.25	0	M,VS
			5	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0		U	0.1	V 5, 0.1
			<u>с</u>	0	0	0	0	0	0	0	0	0	VC	0	0	0	0	0		0	0.75	V 5, 1 VC 0 1
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.75	,	M	0.1	V 3, 0.1
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.75		S. 14	s	~
			1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		VS	0	0
		0	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0.75	0		VS	ő	ő
	lõ	Ŭ	0	õ	õ	0	õ	0	0	õ	õ	õ	õ	õ	0	õ	0	Ő		0	VS.VS	ŏ
	lo		0	õ	õ	õ	õ	0	õ	õ	õ	õ	õ	õ	õ	õ	0	õ		0	0	Ŵ
	Lõ		0	õ	õ	õ	õ	õ	õ	õ	õ	õ	õ	õ	õ	Ő	Ő	Ő		õ	vs	0
	г	0	0	(	0	0	0	0	0	0	0	0	0	0	0	0	0	0	V	S.S. 1	0.5	0 1
		ñ	0	Č	) 0	0	0	0	0	0	õ	0	õ	ő	0	0	ő	ő	VS	V.S. 1	0	NM.0.75
	0	5	s. 0.75	Ċ	0	0	0	0	0	0	õ	0	õ	õ	Ő	0	õ	Ő		0	õ	M.VS
		0	0.25	(	0 0	0	0	0	0	0	0	0	0	0	0	0	0	0		VS	0	0
	(	0	0	(	0 (	0	0	0	0	0	0	0	0	0	0	0	0	0	S,	0.25	0	S
		0	0	(	0 (	0	0	0	0	0	0	0	0	0	0	0	0	0		0	М	<i>S</i> , <i>VS</i> , 0.5
	- 1	0	0	(	0 (	0	0	0	0	0	0	0	0	0	0	0	0	0	<i>S</i> ,	<i>S</i> , 0.5	0.25	0
	- 1	0	0	(	0 (	0	0	0	0	0	0	0	0	0	0	0	0	0	Μ	,0.25	0	0
	- 1	0 VS	S, <mark>S, 0.</mark> 2	25 (	0 (	0	0	0	0	0	0	0	0	0	0	0	0	0		Yes	VS	М
FCM Synthes	is =	0	<u>М,</u> <b>S</b>	(	0 0	0	0	0	0	S	0	0	0	0	0	0	0	0	ς,	0.25	0	М, <b>S</b>
,		0	0	(	0 (	0	0	0	0	S	S	0	0	0	0	0	0	0		0	0.1	<i>S</i> , 0.1
		0	VS	(	0 0	0	0	0	0	S	0	0	0	0	0	0	0	0		VS	0.75	<i>S</i> , 1
		0	0	(	0 0	0	0	0	0	S	0	0	VS	0	0	0	0	0		0	0.1	<i>S</i> , 0.1
		U	0	(	0 0	0	0	0	0	0	0	0	0	0	0	0	0	0.75		S	S	0
		5	0	(	0	0	0	0	0	0	0	0	0	0	0	0	5	0		S	0	0
		0	1		, 0	0	0	0	0	0	0	0	0	0	0	0	0.75	3		3	0	0
		0 <u>/</u> n	v, 0.25		, 0	0	0	0	0	0	0	0	0	0	0	0	0.75	0		<b>ک</b>	U	0
		n	0		, 0	0	0	0	0	0	0	0	0	0	0	0	0	0		M	0	0
	- 17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0

Figure 5.5 FCMs for analysis and synthesis obtained through survey

	ΓO		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	S, 1	0.5	0 1
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	5,1	0	0.75
	0.5	S,	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	S	0	M
	0	М,	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	W,S
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	<i>S</i> , <i>S</i> ,0.25	W	0
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	M,VS	<i>S</i> , <i>VS</i> , 0.5
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	VS, S, 0.5	0.25	0
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	<i>S</i> , 0.25	0	0
	0	VS	.0.25	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	W, S, Yes	0	W
FCM Choice =	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0.25	0	<i>S</i> , <i>S</i>
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0.1	S, 0.1
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0.75	M, S, 1
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0.1	<i>S</i> , 0.1
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0.75	0	S	0
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
	0	1	1,1	0	0	0	0	0	0	0	0	0	0	0	0	0	l.,	0	S	0	0	W
	0	0	.25	0	0	0	0	0	0	0	0	0	0	0	0	0		0.75	0	S	0	0
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	VS	5
	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	W
	- 0		0	0	0	U	0	U	0	0	U	0	0	0	0	0		0	0	0	0	1
		гО	0	0	0	0	0	0	0	0	0	0	(	1	n	0	0	0	0	S 1	05	0 т
		0	0	0	0	0	0	0	0	0	0	0	(	0 (	õ	0	0	0	0	S. 1	S	0.75
		0.5	0.75	0	0	0	0	0	0	0	0	0	(	0 0	0	0	0	0	0	S	0	VS
		0	0.25	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0	S	0	M
		0	0	0	0	0	0	0	0	0	0	0	(	0 (	0	0	0	0	0	S. 0.25	0	0
		0	0	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0	0	M	S. 0.5
		0	0	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0	VS. 0.5	S. 0.25	0
		0	0	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0	M. 0.25	S	0
		0	0.25	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0	Yes	0	0
		0	0	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0	0.25	0	W
FCM_Evaluation	n =	0	0	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0	0	0.1	0.1
		0	0	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0	0	0.75	M. S. 1
		0	0	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0	0	0.1	S.0.1
		0	0	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0.75	0	0	0
		0	0	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0	0	0	0	0
		0	1	0	0	0	0	0	0	0	0	0	(	0 (	0	0	0	0	S	0	0	0
		0	0.25	0	0	0	0	0	0	0	0	0	(	) (	0	0	0	0.75	0	VS	0	0
		0	0	0	0	0	0	0	0	0	0	0	(	0 (	0	0	0	0	0	0	0	VS
		0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	ő	0	TAT
				· · · ·	· · · ·		· · · ·	· · · ·					•		0	0	υ.	0	0	0	U	VV

InputVector = [A P S M R Q EqA EqS Md C PC I PI Imp D Com O T Cost V]

Figure 5.6 FCMs for choice and evaluation obtained through survey

Three different FCM have been collected for every activity type. The respondent had a choice to indicate connector weights in qualitative (W - weak, M - medium, S - strong or VS - very strong) or quantitative manner. It is evident that each respondent has created different task risk behaviour. Consequently, FCM vary depending on risk factors included, their connectors and weights. One respondent considered that one map can be used to represent all activity types. Other two respondents have created considerably different maps for different activity types. Having in mind that the two respondents work in the same project of the same department in a company, it is clear that risk view differs on individual basis and on the stakeholder's role. The obtained FCMs differ also from the general map presented in Chapter 2. However, the solution can support all the adjustment in this area.

It is interesting to notice that the users have expressed the need for functionalities that require more information that is currently demanded in the model. They indicated that it would be beneficial to provide data analysis and to connect risk management with other indicators (like Gantt charts) that would be synchronized automatically. However, the problem that is present in risk management during development process is the lack of data. In production domain, there is a history of data collection that can now be connected with data science to give new perspectives on risk management. The same can't be stated for the development processes. Having in mind that this system is highly socio-technical, multidisciplinary and at the same time area specific, the data are not often collected. Also, the relationships between risk drivers are more often treated in the particular risk scenario than as the part of the system behaviour. Hence, a risk mindset needs to be changed throughout the companies. The users confirm the need for these changes by calling for data analysis and integration with other approaches. In that sense, the solution developed in the thesis can be seen as a bridge between what we want to be the past and the future. The solution divides risk related information to events and system parameters, creates risk behaviour and enables flexible risk assessment. In the initial phase it can use experts for model creation and when the data are available different solutions can be applied to identify behavioural relations: Hebbian or other learning techniques and data mining (like but not limited to MCA that has been performed in Chapter 1). Hence, if the commitment is made, the solution can follow the users through their evolution from expert-related to data-supported risk management.

#### 2.2.2.Result obtained from the test survey – a proper manner to build a process model

Having in mind that the data-supported risk management for development processes has a long way to go before being massively adopted, it is crucial to have a good approach for capturing experts' knowledge. Thus, this section analyses survey results from this perspective.

The respondents have fill in the survey without the prior knowledge on the proposed solution. The relevant information was provided in the survey introduction. The modeler was not present during the survey process. This all has been performed to avoid influencing the respondents with the modeller's experience.

The results have shown that the users can represent their knowledge using the survey. However, explaining the new concepts like the ones in this thesis only through the brief introduction can be overwhelming for the respondents. The effort needs to be made to adopt all the notions used in the approach and in the survey. In industrial environment, this effort can be too demanding and may push the user to abandon the approach. This is paradoxical since it is the users who asked for more concepts and data in the previous section. These may require even more effort than in the current version of the solution. Anyhow, to support the users in their solution adoption it is suggested to conduct a brief introductory session. Preferably, this session is to be perform in person so the users can easily express all the question and potential doubts. After this the survey can be conducted.

Another interesting point that can be observed based on the results is related to the obtained FCMs. One of the reasons why Fuzzy Cognitive Maps have been selected to represent the relationships between the risk factors is because they are cyclic graphs capable of representing feedback loops. By studying different literature resources and risk registers it has been observed that different loops exist between the risk factors. For example, activity performed with the low value can lead to time risk (due to necessary corrections). Time risk can lead to value problems. After the activity has slipped, the solution needs to be found in limited and usually short time leading to the potential problem with the performance quality (value) of the activity. This is the example of a direct loop between value and time risks. Another example may include indirect loops. The time risk can lead to actors' availability problems. Actors availability problem can lead to performance problem and they to the time risk. Hence the loop can be described time – availability – performance - time. Contrary to acyclic graph approaches (Bayesian networks, Artificial Neural Networks), Fuzzy Cognitive Maps are capable of representing and calculating influence of these and other loops presented in the process behaviour. However, only one out of three industrial users who were asked to draw their FCMs have identified feedback loops. Other two users have observed risk factors in the sense of their influence on output risks (cost, time and value). This is in accordance with certain risk approaches (like FMEA) whose main goal is to represent risk in cost and time metrics. Hence, there is a need to mindset change and opining to the feedback relations between risk factors.

It is believed that the introductory session can help users in embracing the relationships between risk factors. Also, the modeller can help users to create their map by analysing with them their risk register and transforming this information into the FCM model. However, this approach can be sensitive to modeler's influence on users. Other option is to conduct the survey using Delphi method so the respondents can discuss their experience towards certain feedback loops. In that case it will be more evident if the feedback loop doesn't exist due to the lack of understanding of the proposed approach or it is the characteristics of a system.

After it has been shown how the survey can be used to collect the information necessary for the risk modelling, the serious game has been developed to bring proposed solution and its concepts closer to the user. This is presented in the following subsection.

#### 2.3. On adoption of the solution

Product model is developed based on frameworks that are well known in engineering community – FBS and FBS-linkage. In that sense, the focus is in their usage in the context of risk management for product development. In order to bring this idea to the users a test serious game has been designed. Currently this serious game focuses mainly on product and its risks. The game includes also notion of problem and solution propagation. It is planned to extend the game to include more process elements that are present in the actual solution.

The game has been made in initial phase of a product decomposition. It includes structural components as nodes, behaviours as flows and functions gathering nodes and flows. While this representation differs from the final product decomposition used in the thesis, it is still based on FBS framework. The observation obtained during this initial game testing are, hence, to be enriched once a new version of the game is developed and tested. Again, as in the case of the process model, the game has been tested on a small group and hence the observations made should be considered as implications and not as hard evidence.

The game had three goals:

- To teach FBS framework how to decompose the product into functions, behaviours and structures;
- To teach risk mapping and propagation through the product;
- To teach collaboration for risk solving having in mind risk dynamics.

The conducted serious game is documented in Figure 5.7. At the beginning, the rules of the game have been explained to the group (see Figure 5.7a). The rules (related to product decomposition and risk propagation) and the play are represented in the rest of this subsection.



Figure 5.7 Serious game: a) introduction of rules; b) product and its structure and flows; c) product with function introduction; d) product and its development teams; e) risk apparition and propagation; f)Problem and solution propagation.

The product has been decomposed into nodes and links forming the structure (see Figure 5.7b). Nodes represented product components and links connection between them (mechanical connections, but also other like cables). Flows between components have been represented as arrows (see Figure 5.7b). Different arrow colour has been assigned to different behaviours. The behaviours have been merged to form functions (see 5.7c). The players form their functions freely and randomly. This is clearly not the case with the real product and its only goal has been to make every game unique.

The players have been divided into groups represented with different pawns. Each group has been in charge for limited number of components and behaviours and functions on top of them. Figure 5.7d shows the groups marking their nodes using stickers.

The risk can randomly appear or propagate. The risk appears on nodes and links (see red circles in Figure 5.7e). The propagation is made through links and flows. Risk has been considered generally. Hence, no different risk drivers have been considered. The risk behaviour has been defined randomly. Every time the player plays it needs to draw a card that will indicate whether there is no risk or new risk has appeared or propagated.

The goal of each group has been to manage their risks under certain rules:

- In order to solve risk, group pawn needs to be on the node/link where the risk is.
- If the risk has taken only one node and that node belongs to the group, the group can solve it alone.
- If risk is on the link, node owners need to agree to solve the risk together.
- If the risk has taken the whole function, all groups partially or fully in charge for the function loose points.
- When the risk is managed points are gained.
- If one node of a multi-node function is taken by the risk all owners need to agree on solving the risk.

Risk solving included move action and risk management. Move action has been necessary to position the pawn to solve the risk. Each move had its cost. The goal of this action is to represent the focus that the development team needs to made to solve particular risks.

At the beginning of the game each group gets certain number of points. Initial risks and pawns are randomly positioned. The game ends when all the risks are solved. The winner is the group with the most points. The game during the play is illustrated in Figure 5.7f.

The game has been tested by 5 PhD students from Polytechnique Montreal. None of the students had a previous knowledge about FBS framework. Their research field didn't include risk management. At the end of the game, the following observations had been made:

- The students expressed capability to use FBS framework for product decomposition and risk representation.
- The game has enabled players to observe risk on the product level and not only on the level of their components.
- Iterative nature of risk management has been demonstrated due to the random risk propagation and reappearance. Hence, process-product interaction has been demonstrated together with the product risk propagation.
- The collaboration between the groups has been an important factor in risk management.

It can be considered that it is possible to illustrate process-product and pure product risk interactions using the proposed serious game. However, it is believed that several sessions are necessary to enable adequate model creation. First session would be conducted as described in this section – serious game would be played on a product that has been already decomposed. Its goal would be to provide adequate risk management and product decompositions knowledge. In the second session, the users would also decompose a simple product (like a hair dryer) before starting the game. During the last session, the users and the modeler would be decomposing the actual product. After that, the game would be used

for risk management. In this way, the users would be ready to apply developed solution independently and to estimate risks using the simulator.

#### 2.4. Conclusions on the identified limitations (and their solutions)

Through the examples shown in the first chapters of the thesis (Chapter 1, 2 and 3) and the ones presented here, it can be stated that the developed solution can answer to challenges of product development. It can consider various development processes and products. Thorough guided surveys and serious games it can support user in their model development, before performing simulation-based estimation of risks. The whole process can help users in acknowledging system behaviour and better understanding their processes and products. Finally, the main strength of the solution is its flexibility through which users can go from expert-centric to data-driven risk management. It shouldn't be forgotten, however, that the proposed method is just the axe. How sharp it is and how fast the tree can be cut down with it depends also on the user holding it.

The next section focuses on the aspect that are not covered in the current version of the proposed solution.

## 3. Perspectives

The research perspectives can be divided into three main categories: general perspectives, data collection and analysis, and model extensions.

Firstly, as a general perspective, it would be interesting to propose the developed solution in the form of online tool. This way the solution would be available to the wider group of users whose feedback can drive the improvements. Also, if agreed, this online tool can be used to collect the information from different development processes. Consequently, it can help in creation of their risk models. This leads to the second perspective – data collections and analysis.

The developed solution proposed general solution for risk management. However, it is necessary to determine how it correlates to the user needs. In that sense, it would be beneficial to follow one or several development project to beginning to end to make observations and data for future use. The observations should be risk event related, but also considering risk factors, drivers and actors' views and behaviours. In this manner it would be possible to obtain comprehensive information that could be used to help in building of process and product models. This could also be done using the previously mentioned online tool. After, different data mining techniques can be used to define parameters of Fuzzy Cognitive Maps. Further, correlation analyses can be used to define the connections between different risk factors or risk events. As it can be seen, this process is concerning more process part of the solution. However, it shouldn't be neglected that these approaches can be used to determine possible connections between product drivers.

In terms of model extensions several options are possible depending again on available information, but also on user needs. Since the model is based on agent-based methodology, any additional modelling on the agent level can be easily included. If considered relevant, human factor models (like learning and forgetting) can be included in the actor's behaviour so the relevant skill parameters can evolve during the simulation. Other option for behavioural extension can include implementation of Rule-based Fuzzy Cognitive Maps. These maps can represent user's perspectives more accurately. Here, the

connections between risk factors are not linear but based on specific rules. The rules can also consider current values of other risk factors before moving from state to state. In that sense, the model can be more sophisticated, but additional effort needs to be made in rule identification.

Another model extension can include operational or decision-making modules. These modules can be implemented in the current model as a separate agent. The characteristic of this agent, however, strongly depend on the need and the rules determined by those needs. Agent-based optimization can be performed within agents. This type of optimization is considered appropriate in a dynamic environment, but the global optimum is not guaranteed. If global optimum is demanded, heuristic or other approaches are more appropriate.

The extension of the model is also possible in terms of identification and classification of the risks. It has been mentioned before that the solution can be used for automatic identification of risks. However, to enable its full potential it would be beneficial to enable post processing of the generated risk that would include clustering, dependency identification. Again, data mining models can be used to support this idea.

Lastly, the solution and its users could benefit from other tools frequently used in the product development. For example, automatic or semi-automatic creation of the product network can be supported by product CAD model or bill of material. Also, it would be interesting to implement the solution as one of the modules of a CAD software so the risk information can be populated and analysed as the solution is developed. The similar integration can be made on the process level through Gantt charts or other enterprise resource planning tools. With these connections the parameters of the model can be updated as the change appears on the main process or product tool. Consequently, the solutions can provide on time and up to date evaluation. If the connection is made with, both, process and product solutions it can be finally considered that the risk management is an integral part of the product development.

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# Appendices

The appendix section contains:

- Appendix A includes literature analyses on process risk management (Appendix A.1), product risk management (Appendix A.2) and design change (Appendix A.3).
- Appendix B includes analysis of Kendrick's (2003) risk register.
- Appendix C includes user guide for the developed simulator.
- Appendix D includes the example of the survey used to gather the information from the users on product risk management approach.

# Appendix A – State of the art

This appendix present in more detail, the identified literature resources. It includes process-related risk management (Appendix A.1), product-related risk management (Appendix A.2) and change management literature (Appendix A.3)

Appendix A.1 – St	tate of the art on the	process-related risk	management	approaches
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Paper	Maturity	Focus	Development process	Risk behaviour	Risk propagation
(Tyson R Browning & Eppinger, 2002)	Tool	Project	Yes	Simulation + DSM	Yes
(Markeset & Kumar, 2003)	Tool	Project and Product	Yes	RAMS + Risk analysis*	Yes
(Kayis et al., 2006)	Tool	Project	Not included	Multi-agent + Bayesian Network	Yes
(Malotaux, 2007)	Methodology	Project	Not included	Evo project management, plan- do-check-act, planguage	Yes
(Danilovic & Browning, 2007)	Tool	Product	Yes	DSM + DMM*	Yes
(Canbolat et al., 2008)	Tool	Project	Not included	PFMEA + Simulation*	Yes
(Kurtoglu & Tumer, 2008)	Tool	Product	Not included	Graph-based Fault Identification and Propagation*	Yes
(Lough et al., 2009)	Tool	Product	Not included	RED – Matrix*	Yes
(Oliva et al., 2010)	Tool	Product	Not included	Probabilistic relational model*	Yes
(Schindel, 2010)	Methodology	Product	Not included	MBSE for FMEA*	Yes
(Dimitrakopoulos & Li, 2010)	Tool	Project	Not included	Stochastic simulation*	Yes
(Aliahmadi et al., 2011)	Tool	Project	Not included	Cooperative game theory + AHP	Yes
(Bassetto et al., 2011)	Tool	Project and Product	Not included	Model for typology of risks - FMECA*	Yes
(Lazzerini & Mkrtchyan, 2011)	Tool	Project	Not included	Fuzzy Cognitive Maps	Yes
(Bosch-Mauchand et al., 2012)	Tool	Project	Yes	Value chains simulator	Yes
(Fang & Marle, 2012)	Tool	Project	Not included	Risk network model + simulation*	Yes
(Patil et al., 2012)	Tool	None	Not included	Business risks based on RED*	Yes
(Struss & Fraracci, 2012)	Tool	Product	Not included	Model-based FMEA*	Yes
(Abdul-Rahman et al., 2013)	Tool	Project	Not included	Fuzzy synthetic + AHP	No

(Marle et al., 2013)	Tool	Project	Not included	Matrix, clustering + partitioning*	Yes
(Konovessis et al., 2013)	Tool	Project	Not included	Data mining + Bayesian network	Yes
(Cedergren & Tehler, 2014)	Framework	None	Not included	Design theory*	Yes
(Goswami & Tiwari, 2014)	Tool	Product	Not included	Bayesian network*	Yes
(Marle, 2014)	Tool	Project	Not included	Project Risk Interactions Management Process*	Yes
(Marmier et al., 2014)	Tool	Project	Design	Decision tree	Yes
(Zhao et al., 2014)	Tool	Product	Not included	Decision Support System: House of Quality, Functional Analysis System Technique, Cost and Risk Analysis Method	Yes
(Fan Li et al., 2015)	Methodology	Project	Not included	Benefit, Cost, Value, Risk framework	Yes
(Malins et al., 2015)	Methodology	Project and Product	Yes	SysML activity models*	Yes
(Rodney et al., 2015b)	Tool	Project	Not included	Model-based approach	Yes
(Ben Said et al., 2016)	Tool	Product	Not included	Bayesian network + FMECA*	Yes
(Mauborgne et al., 2016)	Tool	Product	Not included	System engineering model*	Yes
(L. A. Shah et al., 2016)	Tool	Process and Product	Yes	Value-risk based decision making	Yes
(R. J. Yang et al., 2016)	Tool	Project	Not included	Social network model and analysis*	Yes
(Amine et al., 2017)	Tool	Product	Design	Fuzzy logic + General Weigh Operator	No
(da Cunha Barbosa & de Souza, 2017)	Tool	Product	Not included	Design Structure Matrix	Yes
(Jamshidi et al., 2018b)	Tool	Project and Product	Not included	Fuzzy Cognitive Maps	Yes
(Jahangoshai Rezaee et al., 2018)	Tool	Project and Product	Yes and no	PFMEA and Fuzzy Cognitive Maps	Yes
(Zheng et al., 2018)	Tool	Project	Yes	Bayesian network	Yes
(Gorecki et al., 2019)	Tool	Project	Yes	Papyrus, UML, simulation	Yes
(Shojaei & Haeri, 2019)	Tool	Project / Supply Chain	Not included	Grounded theory, Grey relational analysis, Fuzzy Cognitive Maps*	Yes
#### Product Authors **Element interactions** Calculates **Risk method** decomposition Design-attribute risk Functional integration assessment Functions, risk methodology: search (Vick, 1999) architecture, and Design change factor theory, technical risk component Risk impact factor analysis concepts and systems heuristics System component relationships (spatial, (T.R. Browning, Integration analysis Component energy, information, DSM 2001) (clustering) material) and quantification (T.R. Browning et al., Technical performance Attributes Attributes to activities Risk value method 2002) risk Model-based FMEA, diagnosability (Struss et al., 2002) System models System models diagnosability analysis and models (Tumer & Stone, Functions and Failures Failure modes Matrix-based 2003) components (Papadopoulos et al., FMEA generation Model-based FMEA System diagrams System diagrams 2004) System emergence, (Struss, 2004) Components constraints, parameters, Fault analysis Deviation models variables Model-based Safety (Joshi et al., 2005) System models System models Safety analysis Analysis: system and fault models Function (and Identify failures Function-Failure (Stone et al., 2005) flows) and Failures (modes) Design Method components Direct connection Key characteristics Product performance Taguchi, orthogonal (Nataraj et al., 2006) and functions between the two (variation) arrays Matrix-based (Lough et al., 2008, Function and Failures Centre of risk likelihood and 2009) components consequence Component, Functional interactions. (Schindel, 2010) Functional role, FMEA generation MBSE states Feature Probabilistic **Relational Model:** Components, Flows System functioning Dependability Bayesian network (input and output (Oliva et al., 2010) modelling based on System performance with object and attributes) and activities (reliability) relationships Functions uncertainties, FMEA, FTA D-FMEA (Chan et al., 2012) Quality assurance Markov model (Struss & Fraracci, Qualitative relations over Variables FMEA generation Model-based 2012) variables

#### Appendix A.2 – State of the art on the product-related risk management approaches

Hardware, Software Hardware, Software Hardware, Software architecture and adjacency matrix (no flows)

(Kasthurirathna et al.,

2013)

Robustness

Failure tolerance

(Van Bossuyt et al., 2013b)	Subsystems	System	Trade risk	Risk vector
(Fernandes et al., 2014)	Design variables		Matrix of imprecisions	Imprecision management method
(Goswami & Tiwari, 2014)	Product and Modules	Relationships between functional instances	Overall Enterprise Risk Index	Bayesian network
(Haley et al., 2014)	Functions and variables (behaviours)	Bipartite network	Failure analysis	Centrality and eigenvector centrality
(Lee et al., 2014)	Components		Reliability Cost-benefit analysis	FMEA, FTA, Monte Carlo
(Brunetto et al., 2015) (Estébanez et al., 2015)	Face of design Modules	Direct contact (adjacency)	Complexity Life Cycle Cost Product reliability	Graph Weibull distribution and Monte Carlo
(Luo, 2015)	Components	Interactions – component affect functional performance of another component	Product evolvability	DSM Sumulation Fitness
(Bayar et al., 2016)	Manufacturing system elements, KPIs, parameters	Disruption, disruption features, propagation of disruptions	Expected performance	Immune system inspired Multi-agent EMECA
(Ben Said et al., 2016)	Components		effectiveness	Bayesian networks
(Haley et al., 2016)	Functions and variables (behaviours)	Bipartite network	Behavioural degradation	Topological metrics
(Mauborgne et al., 2016)	System models	System models with hazards	Safety requirements	MBSE-based
(Opgenoord et al., 2016)	Uncertain parameter		Uncertainty	Distributional sensitivity analysis
(Amine et al., 2017)	Design concepts (embodiment design choices)		Maturity, meeting requirements and performance	Fuzzy logic and General order weight operator
(da Cunha Barbosa & de Souza, 2017)	Component and its severity	System component relationships (physical, energy, mass, information) and their occurrences and impact factors	Performance risk	DSM HAZOP Risk Priority Number
(Arlitt et al., 2017)	Functions and components	Flows	Environmental impact	Bayesian approach
(Rambikur et al., 2017)	System models	Architecture	Failure analysis	FTA and System engineering (action diagrams)
(Jiang et al., 2019)	Subfunctions, Principal solutions	Correlation matrix of subfunctions	Performance value	Performance value matrix
(Y. Li et al., 2019)	Component	Function flows (energy, material, information)	Influential function module	algorithm Susceptible-infected- recovered (SIR) model
(Z. Li & Chen, 2019)			Novel FMEA	Fuzzy belief structure and grey relational projection method

### Appendix A.3 – State of the art on the change management

Authors	Focus	Decomposition	Propagation
(Clarkson et al., 2004)	Product	Components	Change Prediction Methods (CPM)
(Ouertani, 2008)	Project (activities)	Product data, feedback and forward arcs, dependency at creation, dependency at modification, redundancy and consistency.	Completeness, variability and sensitivity gives dependency degree. Downstreem
(Hwang et al., 2009)	Product	CAD	Neutral reference model
(Mane et al., 2011)	Product	Systems	Markov model
(Koh et al., 2012)	Product	Components, change options, requirements	MDM, CPM, House of Quality
(Morkos et al., 2012) (Morkos & Summers, 2010)	Product	Requirements	High Order DSM
(Xu et al., 2011)	Product and project	Product components, logistic,	DSM and discrete event
(Hamraz et al., 2012)	Product	FBS linkage	FBS linkage and CPM
(, , , , , , , , , , , , , , , , ,		Product (components), change	e e e e e e e e e e e e e e e e e e e
(Pasqual & de Weck, 2012)	Project and product	(requests) and social layer (communication between actors), actors-to-change links, change-to- component links, component-to-	Multulayer network, Engineer Change Propagation Index, Propagation Directeness
(Reddi & Moon, 2012)	Proiect	actor links Project factors	System dynamic
(F. Vang & Duan 2012)	Product	Parameters	Parameter linkage model
(1.1  ang & Duan, 2012)	Product	Taranteters	and search method
(Koh et al., 2013)	Product	Components Components iterations changes	Step-based CPM CPM MC and Discrete
(Maier et al., 2014)	Project and Product	learning	event simulation
(Wynn et al., 2014)	Project	Components, iterations, changes	Discrete event Product Data
(Do, 2015)	Product	Components	Management database and data mining
(Hamraz et al., 2015)	Product	Function, Behaviour, Structure and links	FBS linkage and CPM method
(Guodong et al., 2017)	Product	Component	Metthew Effect theory
(Ma, Jiang, & Liu, 2017)	Product	Design properties / parameters	search model Multi-variation (concurrent change propagation) propagation based on multi-agent systems.
(Ma, Jiang, Liu, et al., 2017)	Product	Design properties / parameters	Change propagation intensity, optimal change propagation path based on ant colony optimization
(Siddharth & Sarkar, 2017)	Product	Design and manufacturing parameters	No - Design Change Prediction Matrix and Value Prediction Impact
(Eltaief et al., 2018)	Product	Components	CAD management model

## Appendix B – Risk register analysis

Illustrates chronologically how risk factors and their relations have been identified on the Kendrick's (2003).

Appendices



#### Appendix B.1 – Risk register analysis – part 1





Appendices



### Appendix B.3 – Risk register analysis – part 3

# Appendix C - User guide for global risk management simulator

This section presents a short user guide for the developed risk simulator. The goal of this section is not to present all the details regarding software utilization, but rather general overview of it. The potential users can use it to properly represent their development processes and product. Once those are defined Monte Carlo and "what if" analysis can be performed directly in the software.

The user guide focuses on the main solution developed for process-product risk simulation. In order to use the solution, users need to install software AnyLogic (PLE or any other licence). The version 8.5.1 is recommended. If the users would like to create Bayesian networks on their own, they will also need UnBBayes software. In this section, no user guide is provided for UnBBayes software since this tool is used in its original form and purpose. Consequently, all the materials can be found directly in the UnBBayes related resources.

It should be noted that the presented simulator is just one of the outputs of the thesis work. It is a part of a global solution dedicated to the automatic risk prediction and evaluation. Hence, there is still space for the improvement in terms of code optimization and software realization.

The user guide is organized in the following manner. Firstly, the focus is on providing input information. This part, thus, treats how the database (different Excel forms) need to be filled in. After, setting of process and product parameters is presented. Finally, simulation and its results are shown.

#### 1. Setting the input information

Before starting the simulation, it is necessary to fill in all process and product information. All the necessary data are defined in one Excel file. For the global risk management simulator, the name of this file is "ProjectProductDatabase" and it is located in the same file as AnyLogic model (see Figure C.1).

📙   🛃 📜 🗧   ProjectProdu	ictModel			_		×
Fichier Accueil Partage	Affichage					~ ?
$\leftarrow$ $\rightarrow$ $\checkmark$ $\uparrow$ $\blacksquare$ « Utilis	sateurs > Jelena > Models >	ProjectProductModel	ע ט Rec	hercher dans : Pro	jectProd	, p
	Nom	Modifié le	Туре	Taille		
Ruropu	📕 database	15/06/2020 14:58	Dossier de fichiers			
	ExampleV5	26/04/2019 12:15	Fichier PNG	76 Ko		
Telechargeme #	🕌 Jama-1.0.3	29/08/2019 17:17	Executable Jar File	36 Ko		
Documents *	ProjectProductDatabase	08/06/2020 18:15	Feuille de calcul M	44 Ко		
📧 Images 🛛 🖈	ProjectProductModel	08/06/2020 14:23	AnyLogic Model	469 Ko		
📙 Camera						
📙 Chapter V 🛛 🗸					_	
5 élément(s)						

Figure C.1 Model files

Different forms in the "ProjectProductDatabase" file are used to represent different information necessary for model functioning. These forms are presented in the rest of this subsection.

All the information needed can be divided into entity and relational information. Entity tables, hence, define general information regarding particular activities, resources, methods and others. While relational tables define the connections between them. This idea is coherent with the relational database modelling.

#### Entity table: Activity

The essential activity information is defined in "Activity" sheet of the mentioned file. This information is presented in Figure C.2.

ID	Level	Order	Number	Туре	Last	ParentOrder	ParentNumbe	ParentID	InitialCost	InitialTime	InitialValue
0	0	1	1	XX	True	1	1	0	318	129	1
1	1	1	1	Analysis	False	1	1	0	50	5	1
2	1	2	1	XX	False	1	1	0	10	3	1
3	1	2	2	XX	False	1	1	0	10	3	1
4	1	2	3	XX	False	1	1	0	69	54	1
5	2	1	1	Analysis	False	2	3	4	5	2	1
6	2	2	1	Synthesis	False	2	3	4	15	15	1
7	2	3	1	Choice	True	2	3	4	3	1	1
8	2	1	2	Analysis	False	2	3	4	5	2	1
9	2	2	2	Synthesis	False	2	3	4	15	15	1
10	2	3	2	Choice	True	2	3	4	3	1	1
11	2	1	3	Analysis	False	2	3	4	5	2	1
12	2	2	3	Synthesis	False	2	3	4	15	15	1
13	2	3	3	Choice	True	2	3	4	3	1	1
14	1	3	1	SC	False	1	1	0	50	5	1
15	1	4	1	SC	True	1	1	0	60	5	1

#### Figure C.2 Activity information

Activity ID is its unique identifier used every time another agent or a function needs to reference to the particular activity. It can be any integer greater or equal to 0. All the activities have their levels and orders. Level defines the granularity of a process. For example the process on the first level (0 level) includes one activity – development activity. This activity contains all other activities. These activities are in a higher levels (1, 2 or higher) than the process activity. There can be as many levels as necessary. The activities withing the same levels are defined by their order of execution. Hence, the activities with the same order number are executed in parallel. To distinguish them numbers are assigned. Numbers are level and order related. The user hence needs to represent the process activities in the set of levelorder-number. Every process defined as Gantt, IDEF0, BPMN or any other way can be represented in using this triplet. Level, order and number are integers. After, activity type needs to be defined. The available types include: Analysis, Synthesis, Choice, Evaluation, SC and XX. SC stands for synthesischoice. XX is used for parent activities that are comprised of several child activities of different types. It is also necessary to indicate if the activity is the last task in the observed level. This information is represented as boolean. For every activity parent activity needs to be defined. This is performed through parent order, number and ID. Parent level is always child level decreased by 1. Finally, initial cost, time and value are defined. Cost and time are real values greater than 0. Initial value is 1 in most of the cases. If not, it can be any real value in [0, 1].

In "Activity\_MinMax" additional information related to activity risk is defined. This information includes minimal and maximal values of cost and times achieved in the previous projects. Hence, it is used for normalization of risks after FCM calculation. The complementary information is presented in Figure C.3.

activityID	MinTime	MaxTime	MinCost	MaxCost
0	0	0	0	0
1	1	20	2	16
2	1	25	1	20
3	1	13	3	10

Figure C.3 Complementary information related to activity cost and time boundaries

#### **Entity table: Internal resources**

Internal resources and their characteristics are defined in "InternalResources" sheet. This form contains all the information regarding the actors in a company. It can be limited to the actors involved in the project, but it doesn't have to be. The information related to each actor are presented in Figure C.4.

Id	Туре	skill	availability	performance	motivation
0	Project sponsor	0.00	0.50	0.00	0.00
1	Project manager	0.00	0.00	0.00	0.00
2	Team 1 Leader	0.10	0.50	0.00	0.00
3	Team 2 Leader	0.00	0.20	0.00	0.00
4	Team 3 Leader	0.00	0.10	0.30	0.00
5	Team 1 Member	0.50	0.00	0.00	0.00
6	Team 2 Member	0.00	0.10	0.20	0.00
7	Team 3 Member	0.00	0.00	0.00	0.00

Figure C.4 Information related to internal resources

ID is a unique identifier for each internal resource. Apart form this internal resource is described by its type, skill, availability, performance and motivation. Type is the position that the actor is occupying. Skill, availability, performance and motivation are defined as initial potential problems. The value for all these parameters is [0, 1]. Higher the value indicates bigger potential risk. For example, inexperienced worker will have skill and performance values greater than 0. The actual value represents skill or performance of the actual worker comparing to the average worker. This value can be judged by experts or using any HR metrics deployed in the company.

#### **Entity table: Equipment**

General equipment information includes ID, type, availability and support (see Figure C.5). It is defined in "Equipment" sheet. Equipment availability and support represent severity of a potential problems with availability and support. They can be judged by expert or imported from other tools that the company is using to measure these characteristics.

Id	Туре	eq_availability	eq_support
0	Word	0	0.05
1	Excel	0	0.05
2	Mail	0	0.10
3	PPT	0	0.05

Figure	C.5	Equipment	information
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#### **Entity table: External resources**

External resources are defined in "ExternalResources" sheet. They are represented with ID, type, reliability and quality (see Figure C.6). Again, as in the case of internal resources and equipment, reliability and quality represent severities of potential problems and they belong to [0, 1].

Id	Туре	reliability	quality	
0	Customer	0.00		0.20
1	Vendor1	0.10		0.50

Figure C.6 Information related to external resources

#### **Entity table: Methods**

Methods are defined with ID, type and initial value (see Figure C.7). Initial value represents uncertainty related to results obtained by this method. It takes value in the range [0, 1].

ID	Туре	Value
0	Brainstorming	0.05
1	Solution proposition	0.50
2	Link&Equivalence	0.30
3	Choice	0.20

Figure C.7 Method information

#### **Entity table: Controls**

Controls are defined in the same way as methods (see Figure C.8). They possess their id, type and initial value [0, 1]. Initial value can be seen as a quality of information represented by control.

id_control	type	initial_value
0	Standard1	0.9

Figure C.8 Control information

#### **Entity table: Input**

Independent inputs are defined in "Inputs". Again, the main goal is to represent the quality of every input information. This is indicated under value in the same way as for controls. Other input related information includes ID and type (Figure C.9).

id_input	type	input_value
0	input1	0.9
1	input2	0.95
2	input3	0.98

Figure C.9 Input information

#### Entity table: Risk event

Under "RiskEvent" all details regarding hazardous events are defined. Hazardous events are the risk events whose influence is impacting directly cost, time and/or value. All related information is presented in Figure C.10. Apart from the mentioned effects, it is necessary to define the probability of that event and to provide short description.

id	probability	costEffect	timeEffect	valueEffect	description
0	0.05	0	15	0.00	Required end-of phase review was delayed
1	0.06	18	5	0.00	A move from former location
2	0.07	0	20	0.00	An unannounced audit
3	0.05	0	10	0.90	Proprietary data were necessary but owners were reluctant to provide them

Figure C.10 Information related to risk events

#### **Entity table: Structure**

After process-related, it is necessary to define product-related information. This information includes ID, description and initial severities of requirement and technology risks (Figure C.11). For product, risk values are defined in a range [0,1] where 1 indicates no problem and 0 means biggest possible problem.

id	name	requirement	technology
0	F.Geometry	1.000	1.000
1	F.Material	0.970	0.905
2	F.Surface	1.000	1.000
3	M.Geometry	1.000	1.000
4	M.Material	0.960	1.000
5	M.Control	1.000	1.000
6	P.Control	1.000	1.000
7	H.Material	0.990	0.733
8	H.Control	1.000	1.000
9	H.Geometry	1.000	1.000

Figure C.11 Structure information

#### **Entity table: Behaviour**

Product behaviour is defined in the same way as structure (Figure C.12).

id	name	requirement	technology
0	F.Rotation	1.00	1.00
1	F.Aerodynamics	1.00	1.00
2	F.Heat	1.00	1.00
3	F.Noise	1.00	1.00
4	M.Rotation	1.00	1.00

Figure C.12 Behaviour information

#### **Entity table: Function**

Product function is defined in the same way as structure and behaviour (Figure C.13).

id	Name	requirement	technology
0	Generate air flow	1.00	1.00
1	Generate heat	1.00	1.00
2	Mix and focus	1.00	1.00
3	Control level	1.00	1.00

Figure C.13 Function information

#### **Relational tables**

After all entities have been defined, it is necessary to define the relations between them. Several relational tables need to be filled in:

- Next activity
- Activity Internal resources
- Activity External resources
- Activity Equipment
- Activity Methods
- Activity Control
- Activity Previous control
- Activity Input
- Activity Previous inputs

- Activity Risk factor
- Activity Risk event
- Activity Structure
- Structure Structure, Structure Behaviour
- Behaviour Behaviour, Behaviour Structure, Behaviour Function
- Function Function, Function Behaviour

Great majority of these tables connect two entities only using their IDs without any additional information. This is the case with next activity where two activities are connected based on their precedence relationships. Activity is connected in the same way with its resources, equipment, methods, controls, inputs, risk events and structure. Activity connection with previous controls and previous inputs represents the connections between activities. In other words, these tables represent precedence input and control relations between activities. Example of Activity – Previous input table is shown in Figure C.14.

id_activity	ad_input_activity
6	5
9	8
12	11
14	7
14	10
14	13
15	14
7	6
10	9
13	12

Figure C.14 Activity - Previous input relational table

Other relational tables provide additional information. This is the case with the Activity – Risk factor. This table connect activity and its factors to their risk event networks developed in UnBBayes ties and software. Hence, the goal is to define factors impacted, probabilities and their severities (see Figure C.15).

ID	Activity	Factor	probabilityNo	probabilityLow	probabilityHigh	valueLow	valueHigh
0	1	Availability	0.025	0.574	0.401	0.300	0.700
1	2	Availability	0.025	0.574	0.401	0.300	0.700
2	3	Availability	0.025	0.574	0.401	0.300	0.700
3	5	Availability	0.380	0.454	0.166	0.300	0.600
4	8	Availability	0.380	0.454	0.166	0.300	0.600
5	11	Availability	0.380	0.454	0.166	0.300	0.600
6	7	Availability	0.380	0.454	0.166	0.300	0.600
7	10	Availability	0.380	0.454	0.166	0.300	0.600
8	13	Availability	0.380	0.454	0.166	0.300	0.600
9	14	Availability	0.380	0.454	0.166	0.300	0.600
10	15	Availability	0.380	0.454	0.166	0.300	0.600
11	6	Skill	0.364	0.426	0.210	0.150	0.450
12	9	Skill	0.364	0.426	0.210	0.150	0.450
13	12	Skill	0.364	0.426	0.210	0.150	0.450

Figure C.15 Activity - Risk factor relational table

Activity and Factor define the activity and risk factor impacted by Bayesian network. Probabilities for each severity are the result obtained form the network. These different probabilities add to randomness of the task behaviour. If there is no data to apply Bayesian network, expert needs to fill in this table.

Similarly, product relations definition also requires additional information. Here, strength of the relation needs to be defined if it is different form 1. This is applicable for all FBS links. The example of Structure-to-Structure table is presented in Figure C.16.

Structure_id	Connected to structure_id	Strength
0	3	1.00
0	9	1.00
0	11	1.00
3	0	1.00
3	9	1.00
3	11	1.00
5	6	1.00
5	8	1.00
5	10	1.00
6	5	1.00
6	8	1.00
6	10	1.00
8	5	1.00
8	6	1.00

Figure C.16 Structure -Structure relational table

#### 2. Setting the process and product parameters in AnyLogic

After input information has been defined in the database it will be automatically synchronized with the database visible in AnyLogic (see 1 in Figure C.17). The corresponding risk factor information will also appear in risk factors related to the activity (see 2 in Figure C.17). This information is synchronized before each simulation.



Figure C.17 Defining required information in the software

Apart from this, on the activity level user needs to define iteration productivity and information related to the used FCM. Iteration productivity is a parameter (see 3 in Figure C.17). Hence, only its value needs to be entered in the dialog box.

FCM is defined using functions (see 4 and 5 in Figure C.17). Having in mind that different FCM matrices can be defined and used for different task types and/or experts, they all need to be defined in "FCM" function (see 4 in Figure C.17). Each FCM is defined as a two-dimensional array and assigned to different activities based on conditions. This is presented in Figure C.18. The users, hence, need to fill in this information to match their needs and process plan.

Properties 🕮	~
FCM - Function	
<pre>double [][] weightMAtrix1 = new double [][] {{0, 0.9, 0.2, 0.1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,</pre>	0.2 0, 0, 1.9, 0,
<pre>if (id=1){     weightMatrix = new Matrix(weightMatrix1);     else if (id=2    id=3    id=5    id=8    id=11    id=7    id=10    id=13    id=25    id=26    id=27){     weightMatrix = new Matrix(weightMatrix2);     else if (id=6    id=-9    id=-12    id=17    id=18    id=19    id=21    id=22    id=23){     weightMatrix = new Matrix(weightMatrix6);     weightMatrix = new Matrix(weightMatrix6); </pre>	
<pre>} else if (lo=:14    lo=:26){ weightMatrix = new Matrix(weightMatrix14); } else if (id=:15){ weightMatrix = new Matrix(weightMatrix15); }</pre>	
<pre>Matrix output1=inputVector.times(weightMatrix); Matrix output2=output1.plus(inputVector); Matrix output3=output2; for (int i=0; i<output2.getcolumndimension(); i++){<br="">double outputValue=output2.get(0, i); </output2.getcolumndimension();></pre>	~

Figure C.18 Defining different FCM matrices and assigning them to activities

In the same ways as FCM matrices are defined, the FCM input vector needs to be assigned. This is performed under "FCMcalculation" function (see 5 in Figure C.17). The definition of a vector is presented in Figure C.19. The FCM input vector is an array. Each array corresponds to different FCM matrix. Hence, usually we have as many FCM vector types as we have FCM matrices. However, there can be less FCM vector types than matrix types. In the vector, we define which risk factors are included. The order of risk factors in the vector needs to correspond to the matrix. After, vectors have been defined, they need to be assigned to activities using conditions. This is performed exactly in the same way as for the matrices.



Figure C.19 Defining different FCM input vectors and assigning them to activities

Contrary to the process, there is no need for additional information on the product level. All productrelated information has been set in the database.

#### 3. Running the simulator

When all the information has been defined, the user can proceed to the simulation. The simulation can be run in two modes: simulation and parameters variation. Simulation mode includes one random seed run. Parameter variation is a Monte Carlo mode where global analysis is performed. The simulation start is presented in Figure C.20.



Figure C.20 Running the simulator

Example of a result on the activity level is presented in Figure C.21.



Figure C.21 Activity results obtained during simulation mode

The user has excess to all activities and product elements. Hence, every process or product characteristics can be seen. In Figure C.21 we can see normalized value for all risk factors, final values for output risks before and after modification and number of performed iteration. Similarly, current risk values can be seen on product element level. On general level final risks (cumulative risks) can be seen. Product level includes colour coded product model that shows the status of every product element

#### Appendix D – Survey on the solution for process-related risk management

Thank you for taking the time to answer the survey!

The survey in front of you is a part of PhD work entitled "Global risk management in product development projects." In the following text we will explain (in short) the main ideas of this work and if you need further information you can consult the related publication<sup>2</sup> or contact me directly on jelena.petronijevic@ensam.eu.

The goal of this work is to simulate risk related to the project development processes with the focus on the design stage. The risks we observe are limited to time, cost and performance quality of the development process (that we call value in the rest of our work). The main idea is based on the separation between the risk events and the behavior of observed development process. Here, we assume that risk events cause a change in one or more parameters of the observed behavior. The development process's behavior is made of parameters and relations between them. Hence, the change in one parameter causes the behavioral change by propagating through the set of parameters and relations. While risk events are specific and can't be generalized, risk behavior (for the observed problem) is considered general. Hence, the goal of this survey is to build this general development project behavior. And this is where we need your expertise!

We consider that development (design) process is made of tasks. We distinguish 4 types of tasks inspired by the FBS-literature<sup>3</sup>: analysis, synthesis, choice and evaluation. Analysis includes all the tasks where the collecting and interpretation of information for the observed problem is performed (e.g. customer needs identification, but also any task where information is collected and analyzed for certain purpose). Synthesis includes tasks where the solution is developed based on the provided information (i.e. this includes but it's not limited to the partial or full creation of solution). Picking one out of several options is the goal of the choice task. Finally, evaluation tasks include all the tests that are used to compare the behavior of the solution under development to desired behavior.

Each task type has its inputs, resources, methods and controls. Hence, this survey has a goal to define the main parameters and their relations characteristic for each task type. Also, the idea is to determine what kind of specificity is needed to be presented within each task type. For example, does absence of certain actors influence the choice task, is the number of actors performing the task important, etc. In this sense, it is possible to create several sub-types within each task type.

To model the task, we use Fuzzy Cognitive Maps (FCM). Here, within each task, the parameters through their relationships influence each other and the final risks (time, cost and value). All the parameters (including the final risks) are represented as nodes and the relationships between them as weighted arcs. The process of risk calculation is based on propagation of risk between the nodes and the process is iterative. Hence, the goal of the survey is to identify the nodes and the weighted arcs for each task type.

As part of our work, we have conducted a literature review based on which we have identified certain parameters and the connections between them. During this survey you're free to extend/change this list of parameters and to extend/change the connections that we have been identified. Since the proposed FCM has no weights assigned, your goal is to assign the weights based on your expertise. Also, we

<sup>&</sup>lt;sup>2</sup> Petronijevic, J., Etienne, A., Siadat, A., & Bassetto, S. (2019, September). Operational Framework for Managing Risk Interactions in Product Development Projects. In 2019 International Conference on Industrial Engineering and Systems Management (IESM) (pp. 1-6). IEEE.

<sup>&</sup>lt;sup>3</sup> Cascini, G., Fantoni, G., & Montagna, F. (2013). Situating needs and requirements in the FBS framework. Design Studies, 34(5), 636-662.

would like to note that the FCM that we're providing is general and, hence, not made for any of the 4 task types in particular. Any modification you believe is necessary is welcomed.

#### The survey

Estimated time to fill in the survey: 1 hour

#### Identification of parameters

In the following table you can see the parameters that have been identified based on the conducted literature review. The table contains the name of the parameter, description and for each activity type you can choose whether to include this parameter or not. The table is not exhaustive so feel free to add the parameters that you consider important. Please indicate in which the task type(s) the parameters are used.

Parameter	Type of	Description	Included	Included in	Included	Included in
	parameter		in	Synthesis	in Choice	Evaluation
			Analysis			
Time	Output	Used to indicate the risk of the time	Yes	Yes	Yes	Yes
<u> </u>	risk	overrun for the task	*7	*7	37	*7
Cost	Output	Used to indicate budget overruns for	Yes	Yes	Yes	Yes
Vl	TISK Outrout	the task	V	V	Vaa	V
value	output	Used to indicate the output quality	res	res	res	res
Availability	Internal	Availability problem of the human				
Availability	resource	resources involved in the task. The				
	resource	availability problem is measured				
		based on the planned availability.				
Performance	Internal	Performance problem (time related)				
	resource	of the observed task				
Skill	Internal	Lack of skill for the performed task				
	resource	1				
Motivation	Internal	Lack of motivation of the human				
	resource	resources involved.				
Equipment	Internal	Availability problem of the assigned				
availability	resource	equipment.				
Equipment	Internal	Includes all problems related to the				
support	resource	equipment itself (e.g. failures) or the				
		support related to the equipment.				
Vendor quality	External	Problems related to the quality of				
	resource	the provided vendor				
37 1	<b>D</b> ( 1	service/delivered goods.				
vendor	External	the required service/goods				
Innut	Insut	Droblems related to input				
mput	mput	information (How trustworthy is the				
		input)				
Control	Control	Problems related to control (How				
Condor	condor	trustworthy is the control)				
Method	Method	Problems related to method (How				
		trustworthy is the method)				
Project	General	What is the level of dependency				
dependency		between this project and other				
		projects (in terms of resources,				
		information)				
Project	General	How important this project is				
importance		comparing to the other projects that				
		are also in process				
Organization	General	What is the general situation in the				
		turnover between the projects				
		departments )				
		ucparuments)			1	1

Communication	General	General level of communication between the team executing the
		project

Note: All the parameters should be considered as problems/risks in the domain they're representing. The severity of the problem is measured from the value used during the initial planning of the project.

# Please indicate if, in your opinion, the mentioned parameters are used for the defined activity types.

# Indicate new parameters (and relate them to the task types) if you consider necessary. Give the short explanation of the added parameters.

#### The parameters - details

Please answer the following questions:

 Having in mind that all the parameters are representing the problem with the value from 0 to 10 (0 – no problem, 10 – high problem), in case more than one actor (human resource), equipment, vendor, input, control or method is performing/used in the activity what is the best way to represent the value of the group involved? Fill in the following tables.

More than one human resource

Parameter	Calculation (min, max, mean). Choose one.	Other. Elaborate your answer	Your comment
Availability			
Performance			
Skill			
Motivation			

#### More than one equipment

Parameter	Calculation (min, max,	Other. Elaborate your	Your comment
	mean). Choose one.	answer	
Equipment availability			
Equipment support			

#### More than one vendor

Parameter	Calculation (min, max,	Other. Elaborate your	Your comment
	mean). Choose one.	answer	
Vendor reliability			
Vendor quality			

#### More than one input/control/method

Parameter	Calculation (min, max, mean). Choose one.	Other. Elaborate your answer	Your comment
Input (quality)			
Control (quality)			
Method (quality)			

2) Related to the previous question, do you think different calculations are necessary for different activity types?

 $\Box$ No, all the calculations are the same no matter the activity type

□Yes, I think different calculation is necessary for certain/all parameters based on the activity type.

If "yes", please indicate the parameters, activity type and the corresponding calculation based on the activity type.

3) Input and control can be the result of the previously performed tasks or they can be created out of our system. Do you think there should exist separate parameter for input/control (created out of our system) and previous input/control (created as the results of the previous tasks)?
□No, they can be represented as one parameter.
□Yes, they should be represented as 2 separate parameters.

If "yes", please elaborate why.

#### The relationships between the parameters

When all the parameters are chosen, its time to define how they influence one another. In the figure you may see some of the relationships we have previously identified. You can (but you don't have to) use this model as a reference. So, feel free to change the relations if you don't find them appropriate. In order to determine if there is a relationship between the two parameters try asking yourself "If the problem X (parameter X) appears what other problems (parameters) will be impacted?" Then you can draw an arrow(s) between the observed parameter and all the impacted parameter(s). Attention:

- Recursive relationships (parameter influencing itself) are not allowed.
- A influencing B doesn't imply B influencing A. In case A influencing B aand B influencing A two relationships (arrows) need to be defined.



After identifying the existence of the relation between the parameters, it's time to assign the impact for each relationship. The impact ranges from -1 to 1 and you can use the following figure to help you assign the actual impact.



The relationships should be created for all activity types separately (since different parameters have impact each other differently depending on the task). We recommend drawing (gradually and by hand) your parameters and their relationships. After finishing you can send the photo of your work. Optionally you can fill in the matrix that represents your drawing. In the following figure you can see the matrix (with the random value of the weights) representing the general FCM you've seen in the first figure. In case you provide matrix, pay attention to the following:

- The matrix is square matrix with the same columns are rows
- All the elements of the diagonal are equal to zero (due to the no self-influence)

 $Input Vector = [A \ P \ S \ M \ R \ Q \ EqA \ EqS \ Md \ C \ PC \ I \ PI \ Imp \ D \ Com \ O \ T \ Cost \ V]$ 

Others influence availability (A)	) ↓																			
Availability (A) influence on others $\rightarrow$ FCM =	٢O	0.9	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	ן 0.3
	0	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0.9	0	0
	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8
	0.1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0
	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6
	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5
	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5
	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7
	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0
	0.7	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0.5	0	0	0	0
	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3
	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9
	0.4	0.2	0	0.1	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0.8	0.15
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	L 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0	0 1

 $Output Vector = \begin{bmatrix} A^n & P^n & S^n & M^n & R^n & Q^n & EqA^n & EqS^n & Md^n & C^n & PC^n & I^n & PI^n & Imp^n & D^n & Com^n & 0^n & T^n & Cost^n & V^n \end{bmatrix}$ 

Also, keep in mind the question: If this parameter is not included for the particular task, will it impact the existence of other relationships and their weights? For example, is the synthesis task with and without a vendor the same in terms of relationships and their weights or the relationships and weight are different? In case they are different, two sub-types of synthesis task need to be defined (one for the case with vendor and the second one without). In case the relationship doesn't change one single FCM

for the synthesis task will be enough because the difference between these two syntheses will be represented by simply deleting all the relationships coming to and from the vendor parameters in case vendor is not included in the task.

FCM Analysis – upload the FCM for analysis task

FCM Synthesis- upload the FCM for synthesis task

FCM Choice – upload the FCM for choice task

FCM Evaluation – upload the FCM for evaluation task

# Jelena PETRONIJEVIC Maîtrise globale des risques dans un projet de développement de produit

### Résumé

Les projets de développement de produits, dont le processus va de la conception à la fabrication, visent à fournir un produit respectant les caractéristiques souhaitées. La gestion globale des risques dans ce type de développement doit donc tenir compte de tous types de risques : ceux liés au processus ou au produit. Le modèle proposé supporte les interactions au sein du processus de développement et de son produit, mais également aux connexions qui les relient par l'exploitation du cadre FBS. La solution proposée supporte : l'identification, l'analyse et l'évaluation des risques. Un simulateur a été implémenté pour l'évaluation des risques. Cet outil est basé sur : la technologie multi-agents, carte cognitive floue, la simulation épidémiologique et la théorie de la conception. La solution fournit une vue complète de la gestion des risques. Elle permet une représentation ascendante, qualitative et quantitative des risques facilitant leur analyse par les approches : Monte Carlo, multivues et l'analyse "et si...".

Mots clés : gestion des risques, développement de produits, simulation, gestion de projet, interactions des risques

# Résumé en anglais

Development projects, with their processes from design to manufacturing, aim to deliver a product with desired characteristics. Global risk management in the product development should, then, consider all the mentioned aspects: from process to final product. Unfortunately, this is often not the case. The thesis, hence, aims at representing project and process risks and their interactions. The proposed model includes interactions within development process and its product individually, but also those related to FBS framework. The solution focuses on risk assessment and presents identification, analysis and evaluation of risks. Simulator has been developed for risk evaluation. This tool is based on multi-agent technology, fuzzy cognitive maps, epidemiological simulation and design theory. The solution provides comprehensive process-product view on risk management. It enables bottom-up and, both, qualitative and quantitative risk representation. Monte Carlo, multi-view and "what if" analysis provide global risk evaluation.

Keywords: risk management, product development, simulation, project management, risk interactions