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# Methodological and operational framework for the validation and improvement of Cyber-Physical and Human Systems based on modelling and simulation

Milad Poursoltan

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Milad Poursoltan. Methodological and operational framework for the validation and improvement of Cyber-Physical and Human Systems based on modelling and simulation. Automatic Control Engineering. Université de Bordeaux, 2023. English. NNT : 2023BORD0097 . tel-04094941

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THÈSE PRÉSENTÉE  
POUR OBTENIR LE GRADE DE  
**DOCTEUR DE**  
**L'UNIVERSITÉ DE BORDEAUX**

ÉCOLE DOCTORALE DES SCIENCES PHYSIQUES ET DE L'INGÉNIEUR  
SPECIALITÉ : Automatique, Productique, Signal et Image, Ingénierie cognitive

Par Milad POURSOLTAN

**Cadre méthodologique et opérationnel pour la validation et  
l'amélioration des Systèmes Cyber-Physiques et Humains  
basé sur la modélisation et la simulation**

Sous la direction de : M. Mamadou Kaba TRAORÉ  
Co-directrice : Mme Nathalie PINÈDE  
Co-encadrant : M. Bruno VALLESPIR

Soutenue le 03/04/2023

Membres du jury :

M. CARDIN Olivier  
M. CHBEIR Richard  
Mme MICHEL Christine  
Mme PINÈDE Nathalie  
M. TRAORÉ Mamadou Kaba  
M. VALLESPIR Bruno

MCF (H.D.R) à l'IUT de Nantes  
Professeur à l'IUT de Bayonne et du Pays Basque  
Professeure à l'Université de Poitiers  
Professeure à l'Université Bordeaux Montaigne  
Professeur à l'Université de Bordeaux  
Professeur à l'Université de Bordeaux

Rapporteur  
Rapporteur  
Présidente  
Co-directrice  
Directeur  
Co-directeur

# **Titre : Cadre méthodologique et opérationnel pour la validation et l'amélioration des Systèmes Cyber-Physiques et Humains basé sur la modélisation et la simulation**

## **Résumé :**

Jusqu'au milieu du XXe siècle, la conception technologique n'intégrait pas assez la dimension humaine notamment dans les aspects concernant les conditions mentales et sociales. Dans la seconde moitié du XXe siècle, l'imbrication des systèmes sociaux et technologiques a conduit à la naissance d'un nouvel écosystème appelé le « sociotechnique ». L'approche sociotechnique a développé l'idée que l'homme et la technologie doivent être considérés comme un système unifié. La révolution des Systèmes Cyber-Physiques au 21ème siècle et leurs interactions croissantes avec les humains ont renforcé la nécessité de l'approche sociotechnique. Ainsi, elle a donné naissance au nouveau concept de systèmes intelligents, connus sous le nom de Systèmes Cyber-Physiques et Humains (SCPH). L'étude, la conception et le développement de tels systèmes sont complexes et nécessitent d'immenses efforts. La modélisation et la simulation (M&S) sont reconnues comme des outils pratiques et efficaces pour aider les décideurs, les concepteurs et les développeurs. Malgré les avantages du M&S pour le SCPH, les modélisateurs sont confrontés à des défis importants. Parce qu'ils ne connaissent généralement pas la nature de la fusion des environnements sociotechniques et ne savent pas quoi modéliser et comment. La présente thèse consiste à puiser de manière appropriée dans plusieurs disciplines pour tirer parti et intégrer les théories et les méthodes issues de l'ingénierie, de l'informatique, des sciences humaines et sociales pour aider les modélisateurs. Commencant par une analyse approfondie des concepts, de la terminologie et des domaines d'application du SCPH, cette thèse propose un framework à trois couches comprenant une couche centrée sur l'objectif, une couche centrée sur le comportement et une couche centrée sur l'exécution pour faciliter la compréhension, la modélisation et le développement de modèles exécutables de SCPH. Dans la couche centrée sur l'objectif, nous proposons un modèle générique objectif-centré basé sur la théorie de l'activité pour étudier le SCPH en tant que système sociotechnique et créer un modèle conceptuel initial. Dans la couche centrée sur le comportement, nous proposons un modèle générique comportement-centré pour relier le modèle conceptuel SCPH à la spécification d'un modèle de simulation correspondant, en utilisant une forme étendue de l'architecture Croyance-Désir-Intention et un langage de haut niveau pour la spécification des systèmes. Dans la couche centrée sur l'exécution, nous proposons un modèle générique exécution-centré qui implémente le modèle de simulation SCPH en relation avec son cadre expérimental. Le framework est mis en œuvre sur un système de fabrication intelligent. Ce travail n'est pas destiné à un domaine d'application spécifique du SCPH et peut s'appliquer à plusieurs domaines allant des systèmes de santé, aux systèmes manufacturiers et aux systèmes de transport.

**Mots clés :** Cyber-Physiques et Humains ; Modélisation et Simulation ; Modélisation à base d'agents ; Langage de haut niveau pour la spécification de systèmes ; Système Cyber-Physique et Social ; Théorie de l'activité, Le modèle Croyance-Désir-Intention

# **Title: Methodological and operational framework for the validation and improvement of Cyber-Physical and Human Systems based on modelling and simulation**

## **Abstract:**

Until the middle of the 20th century, it was assumed that technology should be considered independently and humans (with mental and social conditions) should follow the given technical structures. In the second half of the 20th century, the intertwining of social and technological systems led to the birth of a new ecosystem called the "socio-technic." The socio-technical approach developed the idea that humans and technology should be considered as a unified system. The revolution of Cyber-Physical Systems in the 21st century and their growing interactions with humans reinforced the need for the socio-technical approach. So, it gave rise to the new concept of intelligent systems, the so-called Cyber-Physical and Human systems (CPHS). The study, design, and development of such systems are complex and require immense effort. Modelling and simulation (M&S) are recognized as practical and effective tools to help decision-makers, designers, and developers. Despite the advantages of M&S for CPHS, there are significant challenges for modellers. Because they commonly are not acquainted with the nature of merging socio-technical environments and do not know what to model and how. The present thesis involves drawing appropriately from several disciplines to take advantage and integrate the theories and methods from engineering, computer, human, and social science to pave the way for modellers. Starting with an extensive analysis of the concepts, terminology, and application areas of CPHS, this thesis proposes a three-layer framework including a Purpose-Centric Layer, a Behaviour-Centric Layer, and an Execution-Centric Layer to assist modellers in understanding, modelling, and developing executable models of CPHS. In the Purpose-Centric Layer, we propose a Generic Purpose-Centric model based on activity theory to study CPHS as a socio-technical system and make an initial conceptual model. In the Behaviour-Centric Layer, we propose a Generic Behaviour-Centric Model to bridge the CPHS conceptual model with a specification of its corresponding simulation model, using an extended form of the Belief-Desire-Intention architecture and the High-Level Language for Systems Specification formalism. In the Execution-Centric Layer, we propose a Generic Execution-Centric Model which implements the CPHS simulation model in relation to its experimental frame. The framework is showcased with an intelligent manufacturing system. This work is not intended for one specific application domain of CPHS and can be used for extensive CPHS applications from health, manufacturing, and transport systems to emergency systems.

**Keywords:** Cyber-Physical and Human System; Modelling and Simulation; Agent-based modelling; High-Level Language for Systems Specification; Cyber-physical and social system; Activity theory; Belief Desire Intention Architecture

## **Unité de recherche**

Laboratoire de L'Intégration du Matériau au Système (IMS) – UMR 5218 CNRS. 351, cours de la Libération 33405 Talence cedex France



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I think, therefore I am.

René Descartes (1596–1650)

*Je dédie cette thèse à toutes celles et ceux qui me sont « chers »*

*I dedicate this thesis to all those who are "dear to me".*

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# Preface

This thesis is submitted for the degree of doctor of philosophy at the University of Bordeaux. The desire for this interdisciplinary thesis has come initially from my long-time appetite for thinking across different frontiers of knowledge. Although interdisciplinary research is exciting and productive, mastering the work is puzzling. In some episodes of such a thesis, when disciplines are crossed, we are exposed to losing stability and intellectual integrity. Dealing with heterogeneous sources, stylistic conventions, mixed methodologies, and manifold theoretical frameworks show just a tiny view of this monster. Hegel believed that we should see progress, not as a straight line but as a zigzag formed such that we encounter obstacles and frustrations and then re-adjust our paths (thesis-antithesis-synthesis formula). It would have been impossible to do this lengthy work on a way full of ups and downs without having lovely supervisors, Professor Mamadou Kaba TRAORÉ, Professor Bruno VALLESPER, and Professor Nathalie PINEDE. Although discussions between disciplines with different referencing systems are overwhelmingly tricky, the amount of support, enthusiasm, and friendship of my supervisors were truly commendable.

To reach this point, I am also indebted to my professors in my computer and industrial engineering masters. Particularly, I am extremely grateful to Professor Malek MASMOUDI, who encouraged and supported me to continue my studies, Professor Khaled MEDINI, who was always available with open arms, and Professor Jean Luc MARI for his exemplary morality and very kind soul. I wish to show my appreciation to my lab mates Professor Yves DUCQ, Professor Julien FRANCOIS, Professor Jean-Christophe DESCHAMPS, and Professor Simon GORECKI, in the IMS laboratory.

I would also like to thank my former colleagues, Mr Abdouljavad RAZI and Mr Guillaume ANDRE. This is an opportunity to thank my scientist friends, especially Bahar NASIRIAN, and all the lovely people I met in Bordeaux, Reza FATHI, Mandana SOLTANI, Maryam IRAVANI, Sia RAJI and Sara NIROUMAND.

Finally, I would like to extend my appreciation toward my brother and sister, Mohsen and Mozghan, and express my sincere gratitude to my parents, who have unconditional love and stood by my side from thousands of miles away.

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# Glossary

N.	Term	Definition
1.	Activity	<i>is a unit of behaviour that bridges the subject (actor) and the object (objective entity).</i>
2.	Adaptation	<i>is behaviour adjustment by responding quickly and appropriately to new stimuli.</i>
3.	Ambient intelligence	<i>is an environment where technology is sensitive and responsive to the presence of people and objects in order to support individuals with information or actions whenever needed</i>
4.	Architecture	<i>is a set of rules, guidelines, and recommendations to define the interrelationships between components.</i>
5.	Agent	<i>is a virtual autonomous entity located in a dynamic environment that can communicate with other agents according to protocols and is also able to perceive and act in order to achieve the goals for which it was designed.</i>
6.	Attention	<i>is a highly valued but limited cognitive ability that notices fixing one's mind upon certain discrete aspects of the world in a limited span of time.</i>
7.	Component behaviour	<i>is the way in which a human or an artefact act. The behaviour of a component refers to a change that may be initiated by internal or external events and lead to events in itself or others.</i>
8.	System behaviour	<i>is observable manifestation of an interaction with a system.</i>
9.	Concept	<i>is a unit of knowledge created by a unique combination of characteristics.</i>
10.	Context awareness	<i>is a sensing process to determine what is happening or changing over entities or the environment that may lead to the appropriate actions</i>

11.	CPHS	<i>is defined as an arrangement of human, cyber and physical systems to perform operations and achieve a specific purpose in a socio-technical environment.</i>
12.	CPS	<i>is an orchestration of computers and physical systems so that embedded cyber parts monitor and control physical processes.</i>
13.	Culture	<i>is shared characteristics and knowledge of a specific group of people that change as time goes on.</i>
14.	Cyber	<i>is a concept used to describe an arrangement of sensors, actuators, computers, and networking infrastructures.</i>
15.	Emotion	<i>is an internal state related to the short duration of experience.</i>
16.	Feedback control theory	<i>is defined as a methodology based on a control loop for changing the behaviour of dynamic systems as appropriate.</i>
17.	Intelligence	<i>is gathering and processing information to exploit opportunities and failure to efficiently use or solve them.</i>
18.	Human behaviour	<i>is a mental, physical and social capacity of individuals or groups of people to respond to internal or external stimuli.</i>
19.	Human-Centred System	<i>is based on providing information, knowledge, or physical assistance to satisfy human needs.</i>
20.	Human learning	<i>is known as a tool to acquire experiences, the results of which are reflected in human behaviour.</i>
21.	Human out of the loop	<i>is a situation when CPS operates independently, but the system needs to be activated by human inputs.</i>
22.	Human-in-the Loop	<i>is a situation in which CPS requires human intervention (e.g., shared control) to become operational.</i>
23.	Information	<i>is any stimuli that have meaning for its recipient.</i>



24. Interaction *is defined as an explicit action taken by an element that may have some effects or impacts on another element.*

25. Interest *is a concrete form in which the need and objective are expressed.*

26. Machine learning *is the capability of an artificial system to improve its performance over time.*

27. Personality traits *is a tendency to show a particular reaction or behaviour under certain circumstances.*

28. Physical artefacts *are means to help the human actor perform physical actions.*

29. Physical system *is a system that follows the physics laws.*

30. Psychological artefacts (signs) *are means utilized by humans to fulfil mental actions.*

31. stimuli *is the occurrence of an action or a change in the world.*

32. Social *is associated with activities in which humans communicate with each other within society.*

33. Socio-technical system *is a system where technical and social systems are complementary, and both are essential for the system's functioning as a whole.*

34. System of Systems *is a system of interest in such a way that its elements are themselves systems and keep their own management, goals, and resources while adopting and coordinating to meet SoS's goals.*

35. Structure *is a representation of relations between system components and brings an overview of concepts to explore a system.*

36. System *is a set of interacting entities that form a structure intended to accomplish some functions.*

37. System environment *is a context determining the setting and circumstances of all influences upon a system.*

38. Technology *is the application of tools, processes, or techniques to practical aims.*

39. Teleology *is the purpose of something in the world.*

## Abbreviations

	Abbr.	
1.	Agent-Based Modelling	ABM
2.	Automated Guided Vehicle	AGV
3.	Artificial Intelligence	AI
4.	Ambient Intelligence	AmI
5.	Augmented Reality	AR
6.	Activity Theory	AT
7.	Basic Reactive Plan	BRP
8.	Belief-Desires-Intention	BDI
9.	Behaviour-Centric Layer	BCL
10.	Bio Cyber-Physical Systems	Bio-CPS
11.	Business Process Model and Notation	BPMN
12.	Cyber-Cyber Interaction	CCI
13.	Component Behaviour Architecture	CBA
14.	Cyber-Physical Interaction	CPI
15.	Cyber-Physical System	C-CPS
16.	Cyber-Physical and Human System of Systems	CPHSoS
17.	Cyber-Physical Production System	CPPS
18.	Cyber-Physical Systems	CPS
19.	Cyber-Physical System of Systems	CPSoS
20.	Cyber-Physical-Social System	CPSS
21.	Cyber-Social Systems	CSS
22.	Discrete Event System Specification	DEVS
23.	Discrete Event System	DES
24.	Execution-Centric Layer	ECL
25.	Experimental Frame	EF
26.	Energy, Matter, People, Information	EMPI
27.	First-Order Logic	FOL
28.	Generic Behaviour-Centric Model	GBCM

29.	Generic Execution-Centric Model	GECM
30.	Generic Purpose-Centric Model	GPCM
31.	Human-Centred Automation	HCA
32.	Human-Cyber Interaction	HCI
33.	Human Factors and Ergonomics	HFE
34.	Human-Human Interaction	HHI
35.	Human in the Loop Cyber-Physical Systems	HiLCPS
36.	High-Level Language for Systems Specification	HiLLS
37.	Human-Physical System Interaction	HPI
38.	Human-System Interaction	HSI
39.	Intelligent Emergency Management Systems	IEMS
40.	Internet of All	IoA
41.	Internet of Things	IoT
42.	Key Performance Indicator	KPI
43.	Modelling and Simulation	M&S
44.	Medical Cyber-Physical Systems	MCPS
45.	The National Institute of Standards and Technology	NIST
46.	National Science Foundation	NSF
47.	Object-Oriented Programming	OOP
48.	Personal Protective Equipment	PPE
49.	Performance Shaping Factors	PSF
50.	Purpose-Centric Layer	PCL
51.	Phase Transition Diagram	PTD
52.	Physical-Physical Interaction	PPI
53.	Remote Elderly Monitoring System	REMS
54.	Smart Emergency Response System	SERS
55.	Social Internet of Things	SIoT
56.	System of Systems	SoS
57.	Skill-based, Knowledge-based, and Rules-based	SRK
58.	System-Model-Simulator	SMS
59.	Socio-Technical System	STS

<b>60.</b>	State-Transition Modelling	STM
<b>61.</b>	Unified Modelling Language	UML
<b>62.</b>	Verification and Validation	V&V

# General introduction

Health, manufacturing, transport, and emergency systems are in the midst of the rapid emergence of intelligent systems. Intelligence denotes gathering and processing information to exploit opportunities and failures efficiently to solve problems (Heylighen, 2017). In this regard, intelligent systems refer to the systems that use a level of intelligence to perceive and respond properly to the changes in the world.

With the impressive advancement of physical, communicational, and computing tools and techniques, intelligent systems are omnipresent to respond more appropriately to various needs. Although technology-based capabilities are evolving dramatically, intelligent systems are not entirely separated from humans. On the one hand, intelligent systems can complement human reasoning and enrich our experience and competencies. On the other hand, humans can train intelligent systems to analyse data, make a decision, or perform actions. Additionally, humans can define the desired outcomes and take responsibility for using intelligent systems. In view of these facts, there is a consensus among experts that despite the coming advanced techniques and technologies, humans will remain influential players in intelligent systems.

## 1. Context

Cyber-Physical and Human Systems (CPHS) open a new window on intelligent systems in which the role and importance of humans are prominent. CPHS tends to shape more sophisticated and human-centred systems within a wide range of applications, from smart homes, intelligent manufacturing systems, and robotic surgery to smart grids. The notions, theories and technological means of CPHS are evolving promptly since, on the one hand, the extension of application areas makes CPHS face novel situations and requirements. On the other hand, different technology classes, such as the Internet of Things (IoT), edge and cloud computing, virtual and augmented reality, wearable and tactile sensors, digital assistants, and collaborative robots, are evolving the CPHS. The applications, notions and technological aspects of CPHS will be discussed in depth in this dissertation.

Although considering humans as a pivotal part of the system brings new opportunities and advantages, but also provokes additional challenges in the design, development, and implementation stages. Modelling and Simulation (M&S) are practical and helpful tools for understanding, designing, analysing, and developing complex systems. In this regard, M&S may lead to new system insights for designers that would not be obtained easily from the original system. It also can enable experts to test new techniques to optimize technology and help managers control existing systems better. Despite all the advantages, developing M&S for CPHSs is challenging and faces significant drawbacks and impediments.

## 2. Problematics and research questions

Modellers should always understand the system under study and know what to model and how. The better the modellers understand the system under study, models are more acceptable and closer to the real system. Understanding the CPHS is the first challenging issue because it should be explored as a socio-technical system where technology and social entities are complementary and intertwined. This is why Kant (2016) states that the interpretation of technology is a substantial challenge in CPHS. It is difficult or even impossible to establish a one-to-one mapping between theories of social sciences and engineering fields for investigating CPHS. Hence, CPHS understanding as a socio-technical system requires combining the knowledge and techniques of social sciences with engineering disciplines. Furthermore, some issues that resided in CPHS, like ethics of technology, human-centred automation and acceptance of technology, should be explained in such a way that modellers can understand and apply them in models. As far as we know, there is no unified structure to converge the views of different disciplines and find a common understanding of CPHS and its related issues. Besides, since CPHS is dynamic and intrinsically has heterogeneous components and purposes, it seems requisite to use multiple modelling formalisms to describe it.

The second challenge is related to the behavioural models of humans and technological tools (tech tools). Once modellers have acquired sufficient knowledge about the structure of CPHS and its ecosystem, they should know how to model the behaviours of CPHS, mainly its components such as humans and intelligent tools. This is error-prone work, particularly for human behavioural models that require immense effort. This is why Busogi (2017) claims that modelling human behaviour has often failed to meet expectations and is generally one of the leading causes of failures in M&S projects.

Simulation is related to the models that behave or operate like a given system over time when provided a set of controlled inputs. The third challenge is related to the execution level. When modellers develop a simulation model, they should be able to convert it to a computer model (software language) that executes the simulation model one or many times to meet M&S objectives (e.g., predicting or observing the CPHS behaviour and performing what-if experimentation). To do this, modellers must ensure that M&S objectives are achievable through simulation models that a simulator can run.

To cope with these challenges, this thesis addresses the following research questions:

1. How can the CPHS in its social-technical environment be characterized for modellers?
2. How can a CPHS be modelled for its simulation?
3. Which executable infrastructure can be designed to support such a simulation model?



### 3. Contributions

We require combining knowledge from various domains to find a solution in the modern world (Epstein, 2021). Using a multidisciplinary approach, we propose a three-layered framework that includes a Purpose-Centric Layer (PCL), a Behaviour-Centric Layer (BCL), and an Execution-Centric Layer (ECL). Our proposed framework is designed to answer all mentioned research questions, as illustrated in Figure 1.

Layers	Models	Research questions
PCL	<ul style="list-style-type: none"> <li>Generic Purpose-Centric Model (GPCM)</li> </ul>	1
BCL	<ul style="list-style-type: none"> <li>Generic Behaviour-Centric Model (GBCM)</li> </ul>	2
ECL	<ul style="list-style-type: none"> <li>Generic Execution-Centric Model (GECM)</li> </ul>	3

*Figure 1 Thesis contributions related to the research questions*

The PCL includes a Generic Purpose-Centric Model (GPCM) to focus on utilitarianism, discover the various dimensions of CPHS and study the system regardless of the application domain. This model is developed based on activity theory (AT), a well-known theory for studying Socio-Technical Systems (STS), that can also enhance our knowledge about CPHS as a human-centred system. The GPCM can break down the CPHS into more readily understood concepts and illustrates how CPHS achieves its purpose in a socio-technical environment. We express GPCM mathematically and denote it using the Business Process Model and Notation (BPMN) and SysML to be useful and practical for modellers.

In the BCL, we discuss the CPHS simulation model and its component behaviours (e.g., humans and technological tools). In this regard, we provide a new architecture for behaviour modelling of CPHS components that can model different behavioural patterns for humans and tech tools from simple to complex ones. Then, by means of the High-Level Language for Systems Specification (HiLLS), we propose the Generic Behaviour-Centric Model (GBCM) that allows modellers to develop a comprehensive simulation model of CPHS.

In the ECL, the Generic Execution-Centric Model (GECM) provides guidelines for modellers to establish Experimental Frames (EFs) through HiLLS formalism and link it to the GBCM. Finally, we show how a simulator (AnyLogic) can run provided HiLLS models (i.e., related EFs and CPHS simulation models).

Our proposed three-layered framework provides CPHS modellers with an M&S road map supported by modelling languages as shown in

Figure 2. This road map has four steps to define the system scope and M&S objectives, analyse CPHS, develop the CPHS simulation model and execute it to reach the objectives.

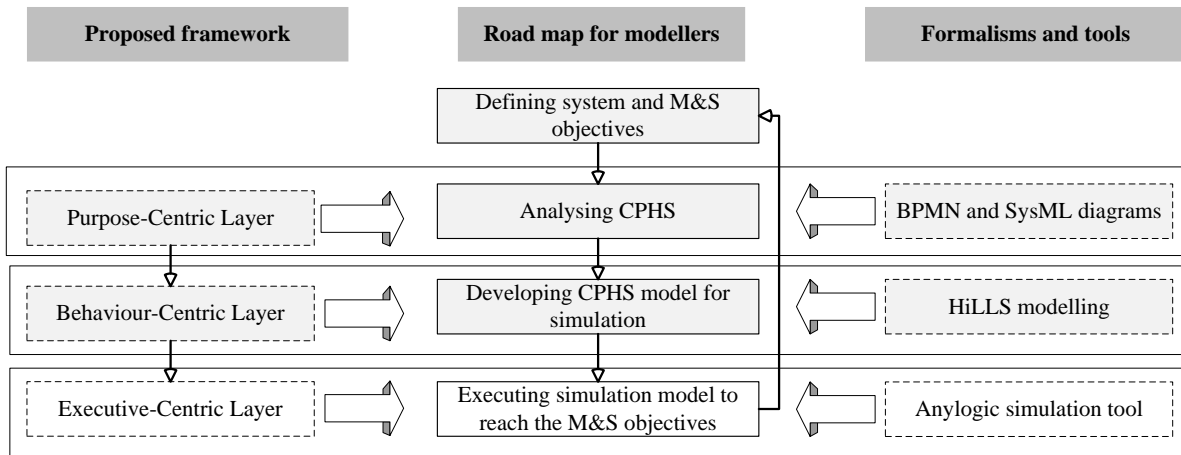


Figure 2 Proposed Road map for modellers

## 4. Structure & Organization

This dissertation is divided into four chapters, as illustrated by Figure 3. The first chapter is dedicated to the state-of-the-art and gives a brief overview of CPHS, its related technologies, and recent proposed M&S frameworks. In the second chapter, we take a look at the theoretical, behavioural, and technical backgrounds that will be used in this thesis. Our contributions will be presented in chapter three. We report our case study in chapter four, and the conclusion and perspectives will be drawn at the end of the dissertation. The dotted arrows in Figure 3 show the relations between chapters, i.e., what concepts and methods in one chapter are used in the other related chapter.

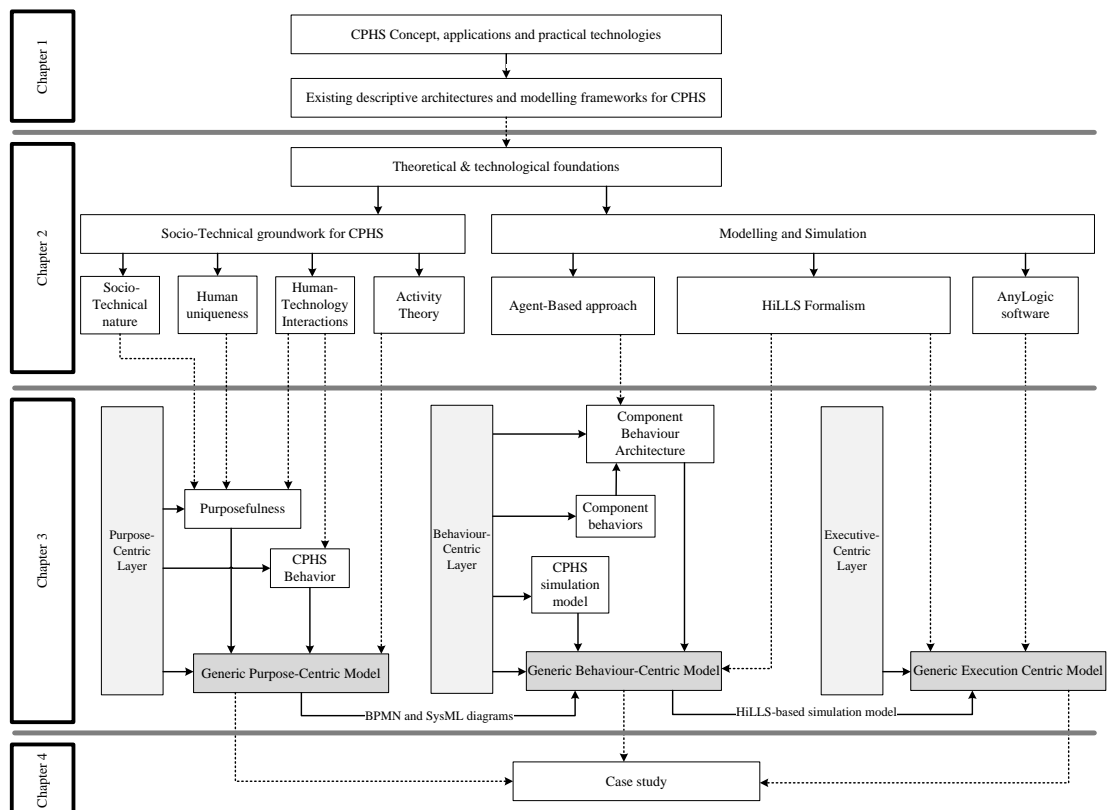


Figure 3 The organization of the dissertation

# Chapter 1

## State of the art

### 1.1 Introduction

Various terms have been used to indicate CPHS as a system. This may be due to the fact that:

- CPHS frequently overlaps with some technologies that may need to be highlighted, e.g., human-like cognitive computation.
- The expansion of usage scope results in the emergence of particular names for specific applications;
- Some usage may put more stress on specific aspect, e.g., social aspects.
- More than one discipline with its own vocabulary gets involved in shaping the concept of this system;

This chapter first looks at the terminology along with concepts because it should be so vigilant about the definition of terms in an interdisciplinary approach. Later, we review some popular forms of CPHS and their applications. Afterward, we explore a series of works investigating the roles of technologies and human beings in CPHS. Finally, we will look into studies providing CPHS frameworks.

## 1.2 Terminology and background review

The history of CPHS originates from Cyber-Physical Systems (CPS), which was coined by the National Science Foundation (NSF) of the United States in 2006 (Lee & Seshia, 2016). One of the ambiguous notions in the term CPS is Cyber. From the etymological way, Cyber is a neologism based on cybernetics derived from the Greek *kubernētēs*, which means pilot or rudder. Cybernetic interconnects the concepts of control and communication tightly (Skyttner, 2001). In a broad sense, the cybernetic approach is associated with a self-regulation mechanism in which a monitor compares what occurs to a system at different time points with some standard, and a controller adjusts the system's behaviour. This approach underlines that information must circulate between the parts of the system and its environment in order to have the system under control. In CPS, the word Cyber is often used in different senses. What Scheuermann (2017) means by cyber is equivalent to the Internet. For Lin et al. (2010), cyber means a computational component to process the information and determine suitable control settings for physical parts of the system. Lee and Seshia (2016) propose the following acceptable definition: Cyber is a concept used to describe an arrangement of sensors, actuators, computers, and networking infrastructures (Lee & Seshia, 2016). From the standpoint of cyber, we can say sensors and actuators associate cyberspace with physical space through a networking approach to control physical actions.

Many definitions can be found for CPS in the literature. NSF describes a CPS as an engineered system constituted from, and depends upon, the tight integration of computing and networking devices, actuation, control, and sensing of the physical world (NSF, 2021). Song et al. (2016) state that CPS is a system using highly embedded computational and communication parts interacting with physical processes to bring new capabilities to physical systems. Another definition for CPS refers to the system that integrates the process of physical reality with computational and communication parts over the Internet (Wang et al., 2015). Nunes et al. (2015) give the following definition: CPS is a system that senses and controls physical phenomena through networks of interconnected devices that collaborate to achieve collective goals. According to another definition, CPS is a set of collaborating computational entities connected closely with the surrounding physical world and its continuous processes (Monostori et al., 2016). A good definition of CPS has been given by Lee (2015). He describes a CPS as an orchestration of computers and physical systems so that embedded cyber parts monitor and control physical processes. In this way, there are feedback in CPS such that physical processes impact computations and vice versa. Although the first usage of the term CPS hinted at the embedded system, the term gradually got a broader sense (Um, 2019). CPS in literature may hint at three different scales of systems. It may refer to a small-scale object (embedded CPS) like a mini-robot, a complex and large-scale system like an airplane, or even a very large-scale system such as a manufacturing system. Small-scale CPSs generally have a centralization nature and operate in a continuous fashion in which input, state, and output

variables are all real values (Martín et al., 2020). Small-scale objects are close to the Internet of Things (IoT) concept. The difference is that IoT paradigm tends to link small objects, first to the Internet and ultimately to each other, while CPS does not necessarily comprise the Internet (Wang & Wang, 2018). In other words, CPS has a tendency to cover physical processes, networks, and computational layers by using various technologies (Peng et al., 2020). So, IoT can be seen as a subset of CPS (Bagula et al., 2021). Nunes and colleagues discuss that concentricity and networking are the basis of the IoT paradigm, whereas CPS highlights the applicability (Nunes et al., 2018). In order to bring humans into play, the term Internet of All (IoA) is used to put not only things but also humans as an essential element in IoT (Nunes et al., 2015). Social Internet of Things (SIoT) is another term employed to describe IoT in which people are envisaged as an integral part of the system (Atzori et al., 2012). In the wide sense, small-scale systems involve humans in design phases (Koreshoff et al., 2013), and then their components follow the physics laws, whereas large and very large scale CPSs have mostly decentralized forms and involve humans in various areas. Zakoldaev et al. (2019) discuss three control schemes on large and very large scales of CPS. They talk over control issues on centralized, decentralized, and hybrid approaches. The server manages all the embedded CPSs in centralized control, while, in decentralized control, the server and embedded CPSs equally control the system. In addition, hybrid control refers to centralized and decentralized control simultaneously.

Traditionally, humans in these CPSs may get involved in various stages (e.g., design, testing, and use) and play roles in and out of the loop CPS (Horváth, 2014). The human inside the loop points to some situations in which CPS requires human intervention (e.g., shared control) to be operational. The human is placed outside the loop when CPS operates independently, but the system needs to be activated by human inputs (Wang & Wang, 2018).

It did not take long to recognize that understanding the human characteristics and prediction of behaviour (including emotions, needs, and intentions) are crucial for the improvement and efficiency of CPS (Mukhopadhyay et al., 2020; Nunes et al., 2018; Sony & Naik, 2020). Since human actions and behaviours are exposed to several environmental and personal factors compared to machines, designing and developing efficient CPSs require much more effort (Yilma, Panetto, et al., 2021). In this regard, more attention was paid to the interrelation of human beings and CPS, resulting in a new concept. Many terms have been used in the literature to refer to this concept. Although most terms stress the interaction of humans in CPS and are employed interchangeably, some subtle differences can be found in their definitions. Cuckov et al. (2017) have used the term Human in the Loop Cyber-Physical Systems (HiLCPS) to highlight the feedback loop between the cyber, human, and physical constituents. Interface development for humans in CPS is typically a subject of interest investigated under the term HiLCPS (Gil et al., 2020; Jirgl et al., 2018; Schirner et al., 2013). Bio Cyber-Physical Systems (Bio-CPS) and Cognitive Cyber-Physical Systems (C-CPS) are two terms putting an accent on the nature of human beings. Bio-CPS explores the biological

interaction between humans and CPS (Fass & Gechter, 2015), and C-CPS gives prominence to the system's cognitive interactions (John et al., 2021). Rahman (2019) used C-CPS to reflect human cognition in CPSS. He used this term to stress human cognition in human-robot interaction. In some cases, C-CPS refers to the CPS having cognitive functions and capabilities to improve human decision-making. One of the most popular terms that emerged around 2010 is the Cyber-Physical-Social System (CPSS). Zeng et al. (2020) believe that the primary purpose of CPSS is to provide services for users. CPSS comprises at least one cyber, one physical, and one social component interacting with each other (Yilma, Panetto, et al., 2021). In other words, CPSS is a CPS closely combined, organized, and integrated with the social characteristics of humans (Wang, 2010; Wang et al., 2019). One of the confusing issues in CPSS is the definition of social characteristics. In a literal sense, the term "Social" is associated with activities in which humans communicate with each other (Cambridge dictionary). However, in CPSS, the word "social" misses the literal meaning and refers to the various aspects of human presence in CPS. Naudet et al. (2018) argue that a CPSS is equivalent to a physical crowd system conditioned by the impact of crowd behaviour. In this regard, social issues, particularly Cyber-Social Systems (CSS), have received significant attention in CPSS. According to Zeng et al. (2020), CSS targets the use of social behaviours and people relationship analysis to bring appropriate information services that significantly enhance people's quality of life. A closer look at CPSS may share the concept of sociotechnical systems. Zhuge (2011) distinguishes between cyber-physical-human space and cyber-physical-socio space. He stresses that direct human-human interaction is only shaped in a cyber-physical-social space that can separately affect cyber and physical space. Yilma, Panetto, et al. (2021) believe that what makes CPSS distinct is paying attention to human needs as well as behavioural, emotional, and cognitive characteristics, which are envisioned to be the three layers for all kinds of interactions. There has been criticism of this label. Using the word "social" may miss the indication of what is unique about human beings. Because human beings are not the only social species and plenty of animals (from ants to elephants) are social as well (Baumeister & Bushman, 2020). Another prevailing term is CPHS. Castañeda Bueno (2017) has applied the term CPHS to point to humans as an active component during cyber and physical interactions and studied them as users in the system. Smirnov et al. (2014) used this term to emphasize real-time interactions between system components. Contrary to the CPSS, which limits itself to the human's social aspect, CPHS considers humans in a broader sense regardless of paying attention to a particular aspect. In addition, unlike HiLCPS, CPHS covers both notions of human in- and out-of-the-loop. In the general form, CPHS is defined as an arrangement of human, cyber and physical parts to perform tasks and achieve specific purposes (Krugh & Mears, 2018; Nunes et al., 2018; Sowe et al., 2016; Zhou et al., 2019).

Other terms used in literature are the following: Human-Centred Cyber-Physical Systems (Ansari et al., 2018; Hadorn et al., 2016), Human-Centric Cyber-Physical Systems (Broy, 2013; Higashino & Uchiyama, 2012; Pinzone et al., 2020) Cyber-Physical Human-Centric

System (Fang et al., 2020) and Human Cyber-Physical Systems (Gelenbe et al., 2012; Netto & Spurgeon, 2017; Zhou et al., 2019).

Since we target very large-scaled systems in several application domains (i.e., manufacturing, healthcare, and transportation) that may focus on different aspects of humans as well as embedded and distributed CPS, CPHS seems to be an appropriate term in this dissertation. Therefore, in the rest of this dissertation, the term CPHS implies the combination of human beings, cyber and physical systems interacting in the different areas of the cyber and dynamic physical world.

There is a large volume of published studies describing the concept of CPS and CPHS as a System of Systems (SoS) (Bondavalli et al., 2016; de C Henshaw, 2016; Yilma, Panetto, et al., 2021; Yin et al., 2020). According to the International Organization for Standardization (ISO15288, 2015), an SOS is a system of interest in such a way that its elements are themselves systems and keep their own management, goals, and resources while adopting and coordinating to meet SoS's goals. Regarding the subject of SoS, some additional terms like Cyber-Physical System of Systems (CPSoS) are seen in the literature, (Díaz et al., 2016).

### 1.3 Terminology synthesis

As can be understood from the previous section, different terms have been used to indicate cyber-physical and human arrangements in the form of a system. Each term generally highlights some particular interactions. Table 1 summarizes pervasive terms and their emphatic points.

*Table 1. Used terms for CPHS and their emphatic points*

	Terms	Primary focus
1.	Human in the Loop Cyber-Physical Systems	The feedback loop between humans and CPSs
2.	Bio Cyber-Physical Systems	Biological interaction between humans and CPSs
3.	Human-Centred Cyber-Physical Systems	Human integrity in a Human-CPS symbiosis
4.	Human-Centric Cyber-Physical System	
5.	Human Cyber-Physical Systems	
6.	Cyber-Physical-Social System	The importance of social characteristics within Human-CPS interactions
7.	Cognitive Cyber-Physical System	Human-like cognitive computation
8.	Internet of All	Human-tools connectivity



## 1.4 CPHS Applications

CPHS has penetrated very large man-made systems and received various perspectives depending on the different requirements of the field. In the following, we review some popular application domains of CPHS in literature and take a look at several reported implementations among endless examples of CPHS.

### 1.4.1 Intelligent Emergency Management Systems (IEMS)

Recently the application of CPHS in Emergency Management Systems (EMS) has received significant attention. Emergency Cyber-Physical-Human Systems (Gelenbe et al., 2012), Emergency Response Cyber-Physical Systems (Estrela, Saotome, et al., 2017), Smart Emergency Response Systems (Kodali & Mahesh, 2017) and Intelligent Emergency Response Systems (Lee & Mihailidis, 2005) are terms used to denote CPHS application for emergency systems.

Two key purposes of EMSs are to find the safest and shortest paths for evacuees in an emergency situation Gelenbe et al. (2012) as well as help emergency crews in rescue and evacuation missions. The components of EMS are generally sensing, evacuees, communications, and decision nodes (Gelenbe et al., 2012). In some cases, human-human interactions, i.e., social interactions among evacuees, may be considered in evacuation systems (Nakajima et al., 2007). With the growing use of smart personal tools, autonomous and teleoperated mobile robots in emergencies, the application of CPHS is extending in this field. The National Institute of Standards and Technology (NIST) of the United States has announced that more than 30,000 firefighters were injured in the USA in 2011 (Smart-fire-fighting 2011). They believe that CPS tools (e.g., smart personal protective equipment, robots, and smart fire department apparatus) can reduce the number and severity of injuries by collecting real-time data, analysing data, distributing and using the results whenever required in operations. Estrela, Hemanth, et al. (2017) used visual sensors and actuators networks to study how to mitigate the flood impacts when water overflows from hydric bodies. Estrela and her colleagues have investigated as well CPS emergency response to reduce environmental damage and life threats in landslide disasters (Estrela et al., 2018).

One well-known intelligent EMS is called Smart Emergency Response System (SERS), presented by the United States in the Smart America Challenge Project. SERS aims to connect CPS technologies with humans in the loop to save lives, rescue people, and meet their essential needs in the case of disaster (Zander & Mosterman, 2014). In SERS, when a call for help is received from cyberspace, a fleet of robots (e.g., a humanoid that carries out heavy lifting to reach dangerous areas), biobots (e.g., dogs equipped with sensors such as cameras or gas detectors), unmanned aerial vehicles (e.g., rotorcraft and fixed-wing aircraft), and autonomous vehicles (e.g., ground vehicles) are sent to the field to perform rescue missions (Zander et al., 2015).

## 1.4.2 Medical Cyber-Physical Systems (MCPS)

Medical Cyber-Physical Systems (Dey et al., 2018), Cyber-Physical Systems in Healthcare (Haque et al., 2014), Healthcare 4.0 (Tortorella et al., 2020), and Cyber-Physical Medical Systems (Banerjee et al., 2011) are the terms used for notable and complex applications of CPHS that are usually deployed to optimize medical services (Tortorella et al., 2020) and improve patients' quality of life (Calderita et al., 2020).

MCPS can be found in varied healthcare applications such as hospitals, assisted living, and elderly care. Depending on the intended purpose, an MCPS may pay particular attention to healthcare staff, caregivers, patients, family members, or a set of them as potential human components of the system. MCPS deploys revolutionary procedures and modern tools (e.g., teleoperated medical devices and assistive and social robots) that offer many new functionalities and practicalities in the healthcare domain, e.g., telecare, Remote Elderly Monitoring System (REMS), Robotic Surgery, and Health Smart Home. In these services, the central role of humans is obvious. For example, Avgousti et al. (2016) draw our attention to the point that a human-in-the-loop control approach is needed to carry out telerobotic operations like those that happened in telesurgery.

In the literature, safety and privacy are two main challenging issues in MCPS (De Mello et al., 2019; Li et al., 2020; Nithya et al., 2018). Since MCPSs are safety-critical systems, the safety requirements at the industrial level are not enough for medical purposes (Fei et al., 2001; Jimenez et al., 2020). Therefore, MCPS should be designed and developed in a safe and reliable fashion (De Mello et al., 2019). Li et al. (2015) deal with risky situations in MCPS and talk about the impact of MCPS on lowering human errors, which are generally complex and difficult to be detected in medical cases.

One of the main practicalities of MCPS is associated with population aging issues. As aging comes, the physical and mental abilities of elders decrease. Thus, there is a call for more efficient systems to ensure the elderly quality of life. Many works can be found dealing with this subject (Geman et al., 2015; Haque et al., 2014; Lapointe et al., 2012; Lee & Kim, 2020; Liu et al., 2019). Since robots represent an opportunity to assist and improve the life quality of the elderly and attenuate social problems, the new generation of robots, the so-called social robots, has drawn much attention recently as a kind of tool in MCPS. Social robots interact with the person by using emotional bonds to provide them with physical and cognitive assistance (Calderita et al., 2020; Salichs et al., 2020). On the one hand, social robots are intended for making long-term interactions with their users (Leite et al., 2013). On the other hand, they should be able to adapt their behaviour to meet the requirements of their users as well (Martins et al., 2019; Sheridan, 2020). For these reasons, social robots call for social learning mechanisms to take new knowledge and skills over long periods through social interactions with users (De Greeff & Belpaeme, 2015).

### 1.4.3 Cyber-Physical Production System (CPPS)

CPS in manufacturing has a range of applications, from supply chain and warehousing systems to production facilities. CPPS refers to the application of CPS in manufacturing systems. Klöber-Koch et al. (2017) state that a CPPS is composed of several lower-scale CPSs related to production. The history of CPPS can be traced back to its preliminary uses of CPS. Yin et al. (2020) used the term CPPS to address social manufacturing in which human and social factors are considered in the CPS architecture.

Industry 5.0, Intelligent Manufacturing Systems, Social Manufacturing, Cyber-Physical Human–Machine Systems, and Smart Factory are also common terms used to refer to the CPPS in literature (Ding & Jiang, 2016; Hozdić, 2015; Jiang et al., 2016; Tilbury, 2019).

Intelligence, connectedness, and responsiveness are three key features of CPPS that bring autonomy, connectivity, and reactionary functions, respectively, to the manufacturing system (Monostori et al., 2016). The prevailing attitude among experts is that despite the advanced techniques and technologies residing in CPPS, humans will keep their considerable roles in manufacturing systems (Becker & Stern, 2016; Pfeiffer, 2016).

Kolbeinsson et al. (2019) assert that collaboration will be more emphasized than automation in the future, and the aim will be to maximize the capabilities of both humans and robots through collaboration. Costa et al. (2019) argue that human integration into CPPS is a challenging task; nevertheless, recent technologies have introduced several solutions to facilitate this integration. In line with this, the need for convergence between humans and CPS in both cyberspace (virtual space) and physical space (real space) has led to a significant shift in strategies at the global level. In 2021, the European Commission presented a new paradigm for future European industry, the so-called Industry 5.0, that emphasizes sustainable, human-centric, and resilient approaches (Breque et al., 2021). Human-centric technologies are pivotal in the industry 5.0 paradigm, where operator enablers are enhanced, and the health of operators are respected (Turner & Garn, 2022). Kaasinen et al. (2022) claim that human operators provide the highest contribution to resilience in industry 5.0. Zhou et al. (2019) argue that CPPS should always be seen as CPS. It seems that the concepts of Industry 5.0 and CPPS are related in the sense that both paradigms refer to a significant shift of manufacturing systems towards the new generation of Human-centered approaches. In the literature, customer involvement and workers' interventions (in and out of the workplace) have attracted much more attention in CPPS. New trends in manufacturing systems such as the aging workforce (who are potentially less flexible and less motivated) (Katirae et al., 2021), remote work (Breque et al., 2021), remote human-robot collaboration (Liu & Wang, 2020; Sultanik et al., 2008) and adaptable Workstations for Human–Robot (Kim et al., 2019) have sparked many new interests in CPPS.

Several studies have attempted to explain operators' future roles in CPPS (Bousdekis et al., 2020; Rødseth et al., 2018; Romero et al., 2016). The health and safety of operators in

CPPS have been explored in the work of Polak-Sopinska et al. (2019) and Sun et al. (2020). Customers' participation in product realization is a popular topic in manufacturing systems. CPPS provides an enabler platform to satisfy customers' needs and desires in a customized way (Tan et al., 2017). Most efforts for product personalization have been carried out by using user-in-the-loop simulation tools as a central technological element. Digital Twin is the most commonly used technology that provides customers with interfaces bringing interactions between the physical and the cyber world and synchronizes the information and functions of the manufacturing systems (Tan et al., 2017).

#### 1.4.4 Transportation Cyber-Physical Systems (TCPS)

CPS has opened new doors to transportation systems. The application of CPS in transportation systems is mentioned in literature by the terms: Intelligent Transportation Systems (Juma & Shaalan, 2020), Transportation Cyber-Physical Systems (Deka et al., 2018), Transportation 5.0 (Wang & Zhang, 2017), and Cyber-Physical-Social System in Intelligent Transportation (Xiong et al., 2015).

The purpose of the TCPS is to collect, interpret and use any transport-related data to control the movement of vehicles and take action to improve traffic efficiency and safety (Guo et al., 2015). It is easy to find a trace of human beings in TCPS. Hence, many studies give fundamental consideration to the social and human aspects of TCPS. Xiong et al. (2015) investigated TCPS by using the CPSS concept. Dhiraj (2019) argues that CPSS-based transportation systems use societal feedback in communication, management, and control of transportation. Henshaw and Deka (2018) discuss that nondeterministic human behaviours may have essential impacts on TCPS, which raises meaningful challenges for the design and development of the system. In this context, Wang and Zhang (2017) deem that human factors and social activities play an influential role in human behaviours and, consequently, the design development and evolution of TCPS. In this line, Pereira et al. (2019) believe that TCPS, in most cases, is tied to human societies at all levels, so society has an equal or even more critical impact than transportation technologies on TCPS. Trapsilawati et al. (2018) have given prominence to several issues concerning human roles in TCPS. They have studied issues related to transparency, degree of automation, adaptive automation, trust and reliance, as well as situation awareness.

TCPS can be broken down into aviation, rail, road, and marine transportation systems (Deka et al., 2018). As to human intervention in TCPS, pedestrians, operators (e.g., drivers and pilots), passengers, crew members, and service staff (e.g., ground staff in the airport) are those who have received more attention. A clear example of CPHS in intelligent aviation transportation systems is given by Sampigethaya and Poovendran (2013). This example is about the control of the aircraft cabin environment to improve passenger comfort and crew efficiency. Cabin windows are equipped with embedded CPS in electrochromic cabin windows

to increase or decrease the level of window transparency. This kind of window uses an electric current to influence gel between two thin glass plates in order to control the light transmission. Such a control can be done by passengers, cabin crew, pilot, and even by altitude sensor in an automated way.

Autonomous vehicles are finding their place in the global market of transportation. The International Organization for Standardization has published the ISO/SAE PAS 22736 standard describing the automation levels for on-road motor vehicles as follows: 0 (no driving automation), 1 (driver assistance), 2 (partial driving automation), 3 (conditional driving), 4 (high driving automation), and 5 (full driving automation). The first four levels involve drivers in driving tasks at different scales, so each one needs to take into account various kinds of human features and behaviour. ECall is an excellent example of TCPS. It is an initiative that the European Union made mandatory since April 2018 in all new cars sold in the union to provide prompt assistance in road collisions. eCall is activated as soon as a severe accident happens and sends a minimum set of data (e.g., location, time, and vehicle's identification number) to the emergency centre and connects the passengers in the car to the emergency centre operator (Chauvel & Haviotte, 2011).

#### 1.4.5 Comparative view of applications

CPHS can be manifested in various applications, each of which underscores specific features of the system. Table 2 recapitulates the features of CPHS in emergency, medical, manufacturing and transport systems.

### 1.5 Overview of contributing technologies and human roles in CPHS

Human beings and technology are entangled in different areas of CPHS. Sowe et al. (2016) discuss that humans impact a CPS through cognition, behaviour predictability, and motivation.

Human behaviour is related to the mental, physical and social capacity of individuals or groups of people to respond to internal and external stimuli. Psychologists have a consensus that human behaviour is a function of situational and individual difference factors. Situational factors can be manipulated, while individual difference variables, such as gender, age, intelligence, and ability, can be measured but cannot be changed in a short time (Baumeister & Bushman, 2020). In other words, human behaviour relies on many factors, like the desire that they follow, abilities they have (e.g., learning), and the situation in which they act (e.g., emergency situation). Human factors and ergonomics (HFE) is a discipline that studies the impacts of physical, psychological, and social characteristics on an individual's performance (e.g., stress, distraction, and fatigue). It is well established that human factors

Table 2. CPHS features in emergency, medical, manufacturing and transport systems.

App.	Other used terms	Main involved groups	Tech tool examples	Highlighted interactions	Main purposes
IEMS	Emergency response cyber-physical system Smart Emergency Response System Intelligent emergency response system Emergency cyber-physical-human systems	Rescuers Evacuees Help-seekers Commanders	Smart personal protective equipment Autonomous emergency vehicles (AEVs) Mobile robotic arms	Human-Human interactions	Help emergency crews in rescue and evacuation missions
MCPS	Cyber-Physical Systems in Healthcare Healthcare 4.0 Cyber-Physical Medical Systems	Patients Healthcare staff Caregivers Patient's family members	Adaptive medical devices Implantable smart sensing Body Area Network	Human-Robot Social interaction Human-Sensor interactions	Improve the effectiveness of care and patients' quality of life by using smart medical treatments and services
CPPS	Industry 5.0 Intelligent Manufacturing Systems Social Manufacturing Cyber-Physical Human-Machine Systems Smart Factory	Customers Operators Engineers Managers	Smart product Collaborative robot (cobot) Automated Guided Vehicle (AGV)	Human-Robot interaction Human-Machine interaction	Bring agility, sustainability, resilience and safety
TCPS	Transportation cyber-physical systems Transportation 5.0 Traffic cyber-social system	Pedestrians, Drivers Passengers, Crew members, Service staff	Autonomous vehicles Vehicle Systems Monitoring Automated Parking Systems	Human-Cyber interaction	Improve traffic efficiency and safety

can influence a large area of human behaviours. Gil et al. (2019) state three main processes of CPHS sensing, decision-making, and action in which human behaviour is emphasized. We conduct a review of the literature according to Gil's processes to understand how humans became affiliated with the system and find out existing knowledge about humans' roles, influencing factors and associated technologies.



### 1.5.1 Sensing and context awareness

Being aware of the situation of entities is one of the most critical features within CPHS (Noor & Minhas, 2014). This information is generally mentioned in the literature as context awareness (Zeng et al. (2020)). The terms "context awareness" and "situational awareness" are primarily used interchangeably in the literature. However, we can find a slight difference in some publications. Context-awareness refers to the awareness about relevant environmental elements, whereas situation awareness is related to being informed about itself. For example, a mobile robot needs to detect the barriers (context awareness) and know its position to reach its destination safely (situation awareness). According to Abowd et al. (1999), context represents any information used to describe the condition of any entity (e.g., human, physical, or cyber object). Thus, context awareness is a sensing process to determine what is happening or changing over entities or the environment that may lead to the appropriate actions (Noor & Minhas, 2014). Abowd and Mynatt (2000) argue that five W questions (who, what, where, when, and why) are a minimal set of needed information about the context. Nahavandi (2019) argues that machines and robots in CPPS must understand human co-workers' actions and future movements for health, safety, and productivity reasons. Smirnov et al. (2014) state that not only CPPS but also all types of CPHSs are context-aware systems. They tried to describe the context of CPHS's components by location, time, individuality, and event. By studying interactions between humans and the IoT, Guo et al. (2013) have discussed three dimensions of context understanding in the form of user, ambient, and social awareness, which refers to the personal, environmental, and social contexts, respectively. CPHS consists of a large number of sensing mechanisms to provide context awareness at different levels. Sensors are common-used devices in CPHS for becoming aware of low-level context. No consensus has been reached regarding the definition of classical sensor and sensing process; however, the proposed definition by ANSI (The American National Standards Institute) still seems to be a suitable description for the sensor. A sensor is a device that provides a usable output in response to a specific measurement (Nomenclature & Terminology, 1975). Sensors utilize a very broad spectrum of techniques to measure a variety of sensing targets. In general, contact, non-contact, and sample removal are three methods applied to measure the values of interest (McGrath & Scanail, 2013). Contact methods require direct physical contact with the intended object that is being sensed (e.g., heart rate sensor), while non-contact sensors do not need any physical contact (e.g., passive infrared sensor). The sample removal methods are generally used when a sample should be gathered and then analyzed using laboratory-based analytical instruments. We can say almost all sensors in CPHS have the form of contact and non-contact forms.

Concerning the frequency of receiving data, Mshali et al. (2018) have classified sensors into the following categories: constant (continuous transmission) like cameras, interval (periodic transmission), for example, electrocardiography sensor which sends heart



performance every 20 seconds, and instant (event-driven) such as active infrared detector which sends data when it detects the passage of a person through the door. Yin et al. (2020) differentiate data sources in CPHS collected from three spaces (i.e., social space, cyberspace, and physical space) by four mechanisms: social sensors, physical sensors, social networks, and sensor networks. Since the new generation of sensors gathers a deluge of data, big data has achieved tremendous importance in CPHS. Debes et al. (2016) categorized nonwearable sensors that are commonly used for monitoring human behaviours (see Table 3).

*Table 3. Used nonwearable sensors for understanding human behaviours source Debes et al., 2016).*

Sensor	Type of Measurement	Task	Usage Example
Passive/Active IR	Motion/Identification	Localization/Presence detection	Detection of a person in the kitchen
Ultrasonic	Motion/Identification	Localization/Presence detection	Detection of a person in the kitchen
Photoelectric	Motion/Identification	Localization/Presence detection	Detection of a person in the kitchen
Video/Thermal	Activity	Localization/Presence detection	Detection of a person next to the stove
Vibration	Vibration	Presence detection/Object usage	Detection of a person in the kitchen
Pressure	Pressure on object	Presence/Fall/Steps detection	Fall detection
Magnetic switches	Door/Cupboard opening/Closing	Objects usage/Presence detection	Cupboard opening
Radio-frequency identification	Object information	Objects usage/Presence detection	TV usage
Audio	Activity	Objects usage/Presence detection	Shower usage
Wattmeter	Consumption information	Electrical objects usage	Water boiler usage

To attain a higher-level context, transmitting a large amount of data from sensors to computing entities is crucial and also a costly and challenging task. Edge computing is a relatively new technology supporting decreasing data transmission and providing a cost-effective way. By taking into consideration edge computing in CPHS, (Sun et al., 2020) have extended the second level of Mitra's context model and distinguished between information acquired from edge computing and deep computing. In other words, to find out the context, they differentiate the data derived from sensors, edge devices (e.g., smartphones), and servers with high computing capabilities (e.g., cloud). Using such an approach, they developed a

layered structure including cognition, modelling, communication, and connection layer to illustrate contextual and technological levels in CPPS. Sahinel et al. (2019) underline that human beings should be considered as a part of context awareness when CPS needs to understand human behaviour and react to this behaviour. The impact of emotions on humans' behaviours and their cognitive and physical abilities are not deniable (Dolan, 2002; Tyng et al., 2017). Thus, emotion-sensing has attracted increasing interest from researchers, particularly in psychological health monitoring, human-computer interaction, and human-robot interaction, to provide deeper insights into understanding human behaviour better. Emotion sensing technologies allow gathering various data, e.g., eye movements, facial expressions, and skin conductance, in order to define an individual's emotional state. Emotion sensing lets social robots establish better understanding and communication with humans (Friis-Liby, 2020). We can take emotion-sensing technologies as a part of ambient intelligence (AmI)(Aarts & De Ruyter, 2009) as well. AmI is an environment where technology is sensitive and responsive to the presence of people and objects to support individuals with information or actions whenever needed (Weber et al., 2005).

Since human states are usually included as essential parts of the CPHS context in industrial, medical, or social scenarios, ethical concerns attract attention because data acquisition about each step and the physical and mental situation of the person may be very disturbing (Nunes et al. (2018). In this line, European Parliament approved the regulation about protecting personal data processing in 2016 to ensure individuals' fundamental rights in the digital age (Regulation, 2016). In addition to ethical limitations, complex endeavours are required to detect the human state (e.g., mood and emotional state) as a significant factor in CPHS (Mukhopadhyay et al., 2020). For example, to better detect the person's emotions (e.g., stress) as an essential part of state context, (Lindgren et al., 2021) have used information related to facial expression, heart rate, breathing frequency, and voice pitch. Li et al. (2015) argue that erroneous human actions in MCPS are complex and need to be detected by using a high-level context inferred from low-level sensory. Mukhopadhyay et al. (2020) call attention to context awareness in the design phase of CPHS, where the real system does not exist, and acquiring big data about entities and the environment may be expensive and often impossible. They proposed a framework to build augmented design models to cope with this issue.

Humans can contribute to the sensing process via two various implications:

- (a) To carry sensors: Although most IoT research has focused on RFID and Wireless Sensor Networks (Truong et al., 2017), CPHS leverages a wide range of sensors, from Ambiance to body sensors. McGrath and Scanail (2013) believe that sensors are fading into the background of human life, and their presence will be more and more passive and routine. There is a considerable application of wearable sensors across CPHS; however, many concerns arise in action. In this respect, a study has been conducted by Schall Jr et al. (2018) to explore the barriers regarding wearable sensors in the workplace, which comprise privacy/confidentiality of collected data, employee compliance, sensor durability, the

cost/benefit ratio of using wearables, and manufacturing practice requirements. Quarto et al. (2017) investigate wearable sensors in the context of MCPS and provide some guidelines for the potential applications. Su and Jia (2021) deployed wearable sensors to study human comfort in autonomous vehicles as part of TCPS.

(b) To provide the system with data/information: Human is widely used as a sensor, also commonly known as social sensing (Wang & Zhang, 2017). This issue stems from the fact that humans possess a wide range of communication tools to create and broadcast massive amounts of information about the physical world. As an information source, humans send information derived from the social space (humans and their observations) to cyberspace to meet various needs (Yilma et al., 2018). Nunes et al. (2018) make a distinction between direct and indirect sensing of humans. Through direct sensing, humans give feedback about sensing targets (e.g., answering direct questions about their feelings). In comparison, indirect sensing refers to a case where we achieve information from indirect human feedback (e.g., recognizing a person's favourite song using playback frequency).

## 1.5.2 Decision-making

Decision-making can bridge sensing and executive action. Context awareness can assist decision-makers (people or machines) in taking action. But, it is not enough for the decisions made by individuals (Chauvel & Haviotte, 2011). Furthermore, it should keep in mind that all decisions do not lead to actions.

The terms decision-making and control generally receive the same meaning in CPHS. Peterson (2017) defines a decision-maker as one who selects an option from a set of alternatives. Decisions in CPHS can be made through humans, technologies (automated decision-making), or hybrid (Munir et al., 2013). Table 4 compares human and AI decision-making provided by Banerjee et al. (2018).

- Human as decision-maker

Siozios et al. (2017) discuss that the decision-making mechanism is a significant challenge for CPS, especially when human-based decisions come into play (usually with rational reasoning) and bring particular concepts such as preference, personal judgment, and beliefs. The decision-making process is one of the most complex mechanisms of human thinking because different factors are involved in it (de Acedo Lizárraga et al., 2007). If we consider decision-making as a task, human beings can do it well as long as they have the opportunity (prerequisites of task), capacity (ability and skills), and willingness (Eskins & Sanders, 2011). Brauner and Ziefle (2019) found that information complexity and individual differences form the overall decision quality. As such, more information complexity leads to less decision speed and accuracy. When a decision-maker is an individual, there are several

Table 4. Comparison of Human decision-making versus AI by Banerjee et al. (2018).

No.	Parameters	Human intelligence	Artificial intelligence
1	Emotions	Human judgment is influenced by emotions	AI-based judgment is not influenced by emotions
2	Intelligence	Human intelligence is stronger in nature	AI is weaker than human intelligence but can be improved by some mechanisms
3	Reasoning	Common sense-based reasoning, philosophical reasoning	Probabilistic reasoning, meta-reasoning
4	Memorization	Humans can recall memorized content easily, but content sometimes might not be complete	AI can recall memorized content faster and more accurately
5	Response time	It depends on the situation	Independent of the situation
6	Cognitive skills	The extremely high degree of cognitive skills	Low cognitive skills, but they can be improved via some mechanisms

issues that can affect their rational behaviours like affective states, emotions and moods. For this reason, human behaviour as a decision-maker is complex. Let us look at an example. In February 2021, an autonomous car was making a right turn at a junction and had the right of way. A human-driven car approaching from the left decided not to stop for a stop sign and collided and hit the autonomous vehicle.

Some emotions seriously impact humans' choices and decisions positively and negatively, e.g., anxiety motivates humans to make more risky decisions (Baumeister & Bushman, 2020). Another example can be mentioned related to the role of motivation in human decision-making. For instance, sending a message at the time of decision-making can motivate humans to make healthy decisions (Shmueli et al., 2014).

Darioshi and Lahav (2021) studied the impact of technology on the human decision-making process. They point to the Digital amnesia phenomenon, which has led people to believe that they are smarter and can make better decisions than they actually make because they think information is easily accessible to them.

By reviewing research articles, Groeneveld et al. (2017) found that the decision-making of humans is shaped based on: rationality (fully input, e.g., data and time), bounded rationality (restricted input, e.g., limited cognitive capabilities), and non-rationality (no available input) paradigms. The bounded rationality and non-rationality for Peterson (2017) are equivalent to decision-making under uncertainty which may hint at decisions under risk (known probability of the possible outcomes) or decisions under ignorance (unknown probabilities).

- IA as decision-maker

Control in CPS is composed of collaborating computational elements that manage physical entities (Park et al., 2015). The concept of control generally refers to the feedback control theory, which is defined as a methodology based on a control loop for changing the behaviour of dynamic systems as appropriate. (Bordel et al., 2017). In classic CPS, computerized

controllers govern physical systems, and humans can be imaginable as supervisors (Salles-Loustau & Zonouz, 2015). Generally, the decision-making of CPS can be performed by computation parts referring to software with a level of artificial intelligence (AI). AI provides the ability to make computers do things (Akerkar, 2014). In this regard, AI spans a vast spectrum of computer decision-making, from programmed functions and machine learning to deep and reinforcement learning. Nunes et al. (2018) used the term Closed-loop CPS to refer to the fully automated CPS control. They give the example of a smart home that monitors the human's exercise levels and decides to set the room temperature at a comfortable level for exercise.

- Hybrid decision making

We can see the trace of both humans and computers in CPHS decision-making. In most CPPS cases, the design is mainly intended to provide decision support to human operators who make the final decision and act (Pacaux-Lemoine et al., 2018). The impact of emotions is present even in hybrid decision-making. For example, obedience as a human psychological factor may play a role in a CPHS in such a way that obedient individuals may be more prone to accept wrong or inappropriate suggestions of the decision support systems in CPHS (Brauner et al., 2016). Khattak et al. (2006) discussed case-based reasoning and expert systems as two decision-making supporting tools for users in ITS. An expert system is a computer system that imitates the decision-making ability of a human expert, while case-based reasoning is recognized as a sub-field of AI using the experience-based approach to solve new problems by applying previous successful solutions to similar problems. Hong and Jiang (2019) address the application of offline and online simulation in decision-making. Recently, Digital Twin has been introduced as a new generation of simulation technology that enables decision-makers to make rapid and more effective decisions in CPHS (Negri et al., 2017). The study of Sheridan and Verplank (1978) has been highly cited in the literature to guide man-computer decision-making. Their proposed automated decision-making levels can also be regarded in CPHS (Gil et al., 2019). Table 5 shows these levels from purely human control to fully automatic systems.

### 1.5.3 Executive action

The result of the decision process may lead physical systems and/or humans to perform physical operations. In CPHS, machines and human beings can act in the physical world.

behaviourism deems that human decision-making processes are usually very complex and hidden, so human behaviours can be studied and analyzed when manifested in the physical world. This is why Walther and Walther (2021) believe that human physical activity is the physical manifestation of aspirations, emotions, and thoughts. The trace of HFE is evident in human action and behaviour. For example, Baumeister and Bushman (2020) argue that humans act better, try harder, and are more motivated in a positive mood than in a neutral mood.

Table 5. Automation of decision-making (Sheridan & Verplank ,1978).

Level	Description	Function
1	Human does all the decision-making task and lets the system implement	<ul style="list-style-type: none"> <li>• Human gets options, selects action and starts the action</li> </ul>
2	System helps by identifying options.	<ul style="list-style-type: none"> <li>• Human requests options</li> <li>• System gets options</li> <li>• Human selects and starts the action</li> </ul>
3	System assists in identifying options and suggests ones that humans may not follow.	<ul style="list-style-type: none"> <li>• Human requests options</li> <li>• System gets options</li> <li>• Human requests action</li> <li>• System selects action</li> <li>• Human select action (may be different)</li> <li>• Human starts action</li> </ul>
4	System chooses the action, and human may or may not do it.	<ul style="list-style-type: none"> <li>• Human requests options</li> <li>• System gets options</li> <li>• Human requests action</li> <li>• system selects action</li> <li>• Human approves or rejects selected action</li> <li>• Human starts approved action</li> </ul>
5	System selects action and in the case of human approvement, it implements.	<ul style="list-style-type: none"> <li>• Human requests options</li> <li>• System gets options</li> <li>• Human requests action</li> <li>• Computer selects action</li> <li>• Human approves action</li> <li>• System starts action</li> </ul>
6	System selects an action, informs the human, and gives him/her a limited time to stop it as needed.	<ul style="list-style-type: none"> <li>• Human requests options</li> <li>• System gets options</li> <li>• Human requests action</li> <li>• System selects action</li> <li>• Human approves action</li> <li>• System starts action either human approves, or human does not disapprove for the given time</li> </ul>
7	System does whole the task and necessarily tells the person what it did	<ul style="list-style-type: none"> <li>• Human requests action</li> <li>• System gets options</li> <li>• System selects action</li> <li>• System starts action</li> <li>• System informs human</li> </ul>
8	System does the entire task, and if the human explicitly requests, the computer tells the human what it has done.	<ul style="list-style-type: none"> <li>• Human requests action</li> <li>• System gets options</li> <li>• System selects action</li> <li>• System starts action</li> <li>• Human may request information</li> <li>• System informs human</li> </ul>
9	System does the whole work and decides what to say to humans	<ul style="list-style-type: none"> <li>• Human requests action</li> <li>• System gets options</li> <li>• System selects action</li> <li>• System starts action</li> <li>• System informs the human if it approves</li> </ul>
10	Computer decides everything and acts autonomously, ignoring the human.	<ul style="list-style-type: none"> <li>• Human requests action</li> <li>• System gets options</li> <li>• System selects action</li> <li>• System starts action if it approves</li> <li>• System informs the human if it approves</li> </ul>



Human actions in STS have been deeply studied because drivers may demonstrate various actions and represent diverse behaviour styles, i.e., aggressive, driving, distracted, normal, drunk, and drowsy (Shahverdy et al., 2020). This comportment is challenging for TCPS and even a nightmare for developing self-driving cars. Because it is so complicated for self-driving cars to find how different road users are likely to behave. Human physical actions in CPHS can be reviewed in individual and collective forms.

(1) *Individual form*: Sowe et al. (2016) have underlined that unpredictability and dynamic motivation are two factors that differentiate humans from artificial components to perform an action. Because on the one side, humans do not always accomplish a task in the same manner, and on another side, without motivation, a person may refuse to do the task. Mubin and Bartneck (2015) discuss how humans react to artificial stimuli that are unpredictable to them. It should be stressed that a human's physical response is usually slower when a stimulus occurs unexpectedly (Karwowski & Zhang, 2021).

(2) *Collective form*: Regarding doing physical actions, human-human and human-robot coactions are two active research topics in CPHS. Human-human collective actions are generally located in the cognitive psychology and philosophy domain (Clodic et al., 2014), while human-robot coactions are chiefly addressed in engineering fields. Since humans are social species, a person's behaviour may cause consequences associated with the behaviour of others. In other words, individual behaviour may be influenced by the actual, imagined, or implied presence of others. Schmitt (1998) believes that social behaviour can differ from individual behaviour such that cooperation, competition, and exchange represent three types of basic social behaviour that cannot be found in an individual alone.

Humans and robots are closely related and can often work in combination and complement each other (Nunes et al., 2018). Gil et al. (2020) underline that creating optimal workload levels for humans interacting with automation to avoid underload and overload should be perceived as a dominant subject in CPHS. There is a large volume of published studies describing human-robot collaboration. Some robots have been developed to be physically attached to humans or worn by humans, e.g., an arm exoskeleton system to increase the human's physical strength (Agah, 2000). The robotic exoskeleton has attracted much attention in CPPS (Bances et al., 2020) and MCPS (Walsh, 2018) to reduce fatigue, prevent injuries and provide rehabilitation. The study of Weiss et al. (2009) has revealed that humans prefer to work with teleoperated robots rather than autonomous ones. To explain this behaviour, Nunes et al. (2018) argue that the reasons may reside in the fact that people are not able to predict the robot's behaviour, and also, they do not know if the robot gives adequate attention to them (lack of presence awareness).

Kolbeinsson et al. (2019) have categorized the collaboration between humans and robots in CPPS into four groups regarding the workplace and task. (1) when human and robot perform a common task in a common workplace, (2) human accomplishes a shared task actively in a common workplace, (3) robot carries out actively a shared task in a common workplace, and

(4) robot and human do a common task but in separate workspaces. Wang et al. (2017) define active, inactive, and supportive roles for the human and robot to do a task collaboratively in individual, multiple, and team forms.

### 1.5.4 Synthesis of human roles

As mentioned earlier, humans can place in different positions within CPHS processes. In most cases, technologies do not eliminate human roles but change or even strengthen them in some cases. Table 6 shows potential human roles in CPHS processes and gives an idea of technologies that can assist humans in performing roles.

Table 6. The role of humans and technology in CPHS processes.

No.	CPHS processes	Human	Technology	
		roles	Main objectives	Examples of human-related technologies
1	Sensing and awareness	<ul style="list-style-type: none"> <li>• Sensor carrier</li> <li>• Data/information provider</li> </ul>	<ul style="list-style-type: none"> <li>• Provide better awareness</li> </ul>	<ul style="list-style-type: none"> <li>Touch sensor</li> <li>Sound sensor/processing</li> <li>Temperature sensors</li> <li>Pressure sensors</li> <li>Passive/active IR</li> <li>Ultrasonic sensors</li> <li>Video processing</li> <li>Smoke sensors</li> <li>Heartbeat Sensor</li> </ul>
2	Decision making	<ul style="list-style-type: none"> <li>• Decision-maker</li> </ul>	<ul style="list-style-type: none"> <li>• Improve decision quality</li> <li>• Effortless decision making</li> </ul>	<ul style="list-style-type: none"> <li>Offline simulation</li> <li>Online simulation</li> <li>Case-based reasoning tool</li> <li>Expert system</li> <li>Augmented reality</li> <li>Extended Reality</li> <li>Virtual reality</li> <li>3D virtualization</li> <li>Digital Twin</li> </ul>
3	Acting	<ul style="list-style-type: none"> <li>• Actor</li> <li>• User</li> </ul>	<ul style="list-style-type: none"> <li>• Effortless physical actions</li> <li>• Human rehabilitation</li> <li>• Human empowerment</li> <li>• Low-risk physical actions</li> <li>• High-quality actions</li> </ul>	<ul style="list-style-type: none"> <li>Social Robots</li> <li>Robot Assistant</li> <li>Robotic exoskeleton</li> </ul>

## 1.6 Literature review of CPHS's frameworks

Architectures and frameworks are helpful leverages to understand and model the systems. In the following, we will look into studies providing frameworks for CPHS. Since the



objectives of the proposed frameworks in the literature are not the same, we classified the frameworks into descriptive and M&S frameworks. Descriptive frameworks are theory-based models that argue how illustrative structures bring more knowledge about CPHS. In comparison, M&S frameworks aim to specify and construct meta-models and make a foundation to model the functionalities of CPHS and develop simulation models.

### 1.6.1 Descriptive frameworks for CPHS

In recent years, there has been an increasing amount of literature on descriptive models and interpretive architectures of CPHS. However, the discussions on descriptive frameworks for human-centred systems are not a contemporary topic. Mumford (2000) argues that using a socio-technical approach assists designers in creating humanistic and effective complex systems. He believes that means are as important as the end, and if there is an intention for humanism ends, the socio-technical approach is a helpful tool. Kroes et al. (2006) define an STS as a system where technical and social systems are complementary, and both are essential for the system's functioning as a whole. Kay (2002) believes that STS can be seen as a class of complex adaptive systems.

Durst et al. (2020) proposed an activity theory-based framework for the analysis and design of socio-technical systems. Their framework has served as a conceptual tool to envision technical, social, and organizational factors for studying socio-technical systems. Carreras Guzman et al. (2020) stressed that CPHS should be conceived as a particular type of socio-technical system. Brauner and Ziefle (2019) had a look at CPPS from a socio-technical perspective (including structure, people, tasks, and the physical parts) and conducted two behavioural studies on human decision-making.

A theoretical CPS architecture has been given by Ahmadi et al. (2018) to enhance CPS-enabled smart manufacturing in Industry 4.0. This architecture is based on the physical, computational/cyber, and human components interconnected by interfaces to attain a common goal of CPS in manufacturing. However, it remains a generic architecture focusing on the identification of entities and their relationships at the sole static organization level.

Oks et al. (2019) presented a reference architecture for designing CPS demonstrators, mainly focused on industrial applications. This reference architecture first determines the objectives, components, and attributes, then specifies scenarios and the demonstrator configuration. It intends to be a helpful structuring factor in assembling existing modules that can be required for the design of a CPS demonstrator, including simulation modules. It is not intended to help derive these simulation modules nor to provide a guideline for the design of such modules.

Smirnov et al. (2014) proposed an upper-level ontology for CPSSs. Their ontology focused on two types of resources and tried to show the self-organization of CPHS resources; however, this study did not take into account CPHS's process and their dynamicity (e.g., learning).

Kozsik et al. (2013) deemed CPS from a workflow perspective, so they considered everything as a task and tried to explain how components behave with regard to constraints. Although their approach can explain how CPS works at the upper level, it cannot show how the system's internal processes operate. The work of Zeng et al. (2020) is another study using hyperspace flow (data flow, physical flow, and human flow) to describe interactions in the design of CPHS. They used a layer Petri Net to denote the control flow of the system. The major drawback of this approach is that it emphasized more on the interactions and states of CPHS components (active and inactive) rather than the process approach. This results in structural difficulties in complex systems in which many interactions occur at the same time.

Gil et al. (2020) zoomed in on CPHS design. They made an effort to provide a method by focusing on the control strategies and interactions to help designers determine how the human and the system should collaborate. They paid attention to human factors in the form of opportunity, willingness, and capability. The limitation of their work was that only humans were considered as users interacting with CPS, and the role of humans in sensing, as well as the concept of human and machine learning, were not regarded.

Yin et al. (2020) proposed a seven-layered framework based on the 5C-level structure already presented by Lee et al. (2015) for CPS. These seven layers point respectively at connection, conversion, communication, computation, cognition, configuration, and collective intelligence. This framework shows the integration of cyber, physical, and social space within each level flawlessly. However, a key limitation of this framework is that the concept of SoS and nested CPHS are not illustratable. Besides, the analysability of components and purposefulness of the interested system is not fully realizable. Moreover, the role of humans in physical actions has not been investigated in the framework.

Yilma, Panetto, et al. (2021) conducted a comprehensive literature review on CPHS and provided a multi-dimensional view of CPHS. They presented a high-level systemic model as a foundation for designing a CPHS which demonstrates key systemic concepts. This model has been depicted by UML 2.0 notation and formalizes a CPHS in the frame of relation, behaviour, function, structure, objective, interface, and environment. The model does not engage with all levels of CPHS in practice, and mid-level and low-level concepts are lacking.

Berger et al. (2020) presented a generic model to describe the architecture of a CPHS, which focuses on human-machine collaboration and intends to help designers determine needs, tasks, and activities in a CPHS. They characterized a CPHS task by using SRK (Skill-based, Knowledge-based, and Rules-based), DIK (Data, Knowledge, and Information), and AADA (Acquisition, Analysis, Decision, Action) models. They recognized that the generic architecture is the first version to improve and indicated a list of future works and challenges to address. Despite its simplicity and efficacy approach, it suffers from several major drawbacks, such as human factors and the social aspect of CPHS.

Kotronis et al. (2019) introduced a model-based approach to identify and satisfy the requirements and concerns of humans involved in CPHS. They used three interconnected

views (i.e., human, criticalities, and system) to extract human needs, transform them into system criticalities, and integrate system criticalities into system structure. Their model focuses on human design requirements but does not help to have a broad look over CPHS structure, components, and processes.

Yilma et al. (2019) provided a meta-model of cyber-physical social systems (CPSS) by defining social, physical, and cyber components and the emerging interactions between components. They pointed out that the formation of CPSS needs a connection between one social component and a physical component that is associated with, as a minimum, one cyber component. Similar to the works previously presented, the approach adopted here focuses on the architectural organization of a CPHS to emphasize its human-centric aspect and how to guide the CPHS designer in identifying and well structuring a custom solution.

### 1.6.2 CPHS modelling frameworks

M&S of CPHS is multi-dimensional (Tao & Zhang, 2017); thus, it may seek multiple abstraction levels for modelling as well as non-fixed simulation scope to meet hierarchical goals. In broad terms, a conceptual model is the most abstract model that serves as a representation of a system for both thinkers and modellers. However, a simulation's conceptual model is something else. It is a descriptive model showing how a developer should develop a simulation to meet the requirements (Pace, 2000).

Due to the lack of laboratory tools to design and experiment with large CPHS, M&S attempts have mainly applied to CPS engineering in order to evaluate complex behaviours and emergent behaviours. Mittal and Tolk (2019) discussed the complexity of M&S applications for CPS engineering. They believe that CPSs are multi-agent systems, and the CPS models should be regarded as hybrid systems using both continuous and discrete systems. They characterized three aspects of CPS agents (intelligence, adaptation, and autonomy) in a broader context. However, no metamodel or methodology is proposed to derive a CPS simulation model.

Hehenberger et al. (2016) looked at a CPS from different angles and noted that cloud-based systems like IoT and distributed CPS call for more M&S abstraction levels. They identified three concerns regarding the M&S of CPS. The first concern is the modelling of the components from different disciplines, while the second one is the modelling of interfaces among components, and the third one is about model integration. While their work focuses on methods and applications for the design, modelling, simulation, and integration of CPS, the authors recognized the lack of a roadmap or guideline of development and the absence of a social dimension (which takes CPS to CPHS).

Weyer et al. (2016) discussed the M&S of CPS-based factories and targeted the dynamic design, particularly for virtual commissioning. They proposed a reference framework having three tiers: applicators, information interface, and data acquisition. These tiers contain the

simulation models for each CPS and their data sets, which are aggregated at the CPPS level to support end-users. This reference framework is intended to enable a seamless connection of vendor-specific CPS and the sharing of their simulation-based models rather than supporting the synthesis of such models.

Similar various efforts with the same limitations of CPS M&S exist in the literature, such as the ACOSO (Agent-based Cooperating Smart Objects) approach by Fortino et al. (2016), the generic conceptual architecture covering CPS modelling from the business level to the infrastructure level, by Dumitrache et al. (2017), the CPS Conceptual Model presented by the CPS Public Working Group (Griffor et al., 2017), and the integrated multi-level and parallel and distributed simulation approach by D'Angelo et al. (2017)

Kotronis et al. (2019) introduced a model-based approach to integrating the requirements of humans involved in CPHS into the design process. To do so, they used Business Process Model and Notation (BPMN) and Systems Modelling Language (SysML) to investigate CPHS design and determine discrete views representing both humans and the system. Even if they suggested deriving from the system view an evaluation model for simulation, this is done in an ad-hoc way and not following a generic mapping scheme between their SysML-based system model and their evaluation model.

A modelling framework has been developed by Albaba and Yildiz (2019) based on merging Bayesian networks (the probabilistic foundation of the method), game theory (a mechanism to produce strategic behaviour expected from human interactions), and reinforcement learning (a learning model for successive human actions).

## 1.7 Conclusion

Although various terms have been used in the literature to indicate an intelligent system that includes cyber-physical components and humans, all of them somehow stress the interactions between humans and technological tools (see Table 1.). We selected the term CPHS within this thesis, which is not limited to specific interactions between humans and tech tools and can cover both individual and social aspects of humans as well. To be clear and avoid getting lost in different interpretations, we define CPHS as a system consisting of cyber, physical systems as well as at least one social entity and one Cyber-Physical Systems (CPS) that performs operations to achieve specific goals in a socio-technical environment.

Human-tech tools interactions are the foundation of future intelligent manufacturing, transportation, emergency, and medical systems. Each CPHS application brings a specific group of people and tech tools into the system and puts more emphasis on specific interactions between humans and tech tools (see Table 2.). Regardless of the field of application, human interactions with technological tools occur within the process of sensing, decision-making, and physical operations. Table 6 displays the roles of humans and technologies involved in CPHS processes.

Among various proposed descriptive frameworks to explain CPHS in the literature, two

approaches have been highlighted to develop explanatory models. The first approach relies on a system view using socio-technical models, and the second one aims to describe CPHS by identifying and classifying the interactions that take place in the system. Our GPCM will tie both approaches, explain CPHS from a socio-technical perspective, and determine human-tech tool interactions.

M&S frameworks for CPHS have been generally developed based on CPS structures. This is why human behaviour modelling is mainly a missing part of the M&S of CPHS. Our GPCM will cope with this issue and provide modellers with a generic behavioural model applicable to human and technological tools.

## CHAPTER 2

# Theoretical & technological background

### 2.1 Introduction

In this chapter, we review the background of theoretical and technological knowledge, which will be employed later in this dissertation. Since this is a multidisciplinary thesis, we tried to keep our interdisciplinary approach to investigating ideas during the review. In this regard, the concepts and theories that will be surveyed in the following may have their roots in different fields of science. As shown in Figure 3, these concepts, theories and technics will support our framework and substantiate our approach within our contributions. In this chapter, we focus on two subjects. First, we tackle the socio-technical foundations of CPHS to understand the CPHS ecosystem and stressed issues. Then, we explore the M&S approach and related techniques, which seem to be pragmatic for the M&S of CPHS.

### 2.2 Socio-Technical Groundworks For CPHS

This section will discuss human uniqueness and give an overview of Socio-Technical evolution. Then we will survey the highlighted issues in human-technology interactions and tackle the socio-technical nature of CPHS. Finally, we will review the activity theory as a socio-technical architecture to analyse human-centred systems.

### 2.2.1 Human uniqueness

We are on a quest to know human nature and the features making human-being dramatically unique. Although scientists have a strong consensus on humanity's distinctiveness from other species, what capacity makes humans unique remains a topic of intense debate. Many attempts have been made to identify the uncommon ability of human beings. Tool use, learning, communication, culture, and social behaviour can be found among reported capacities. Waller (2015) contends that traces of exaggeration can be found in all capacities because we can see these abilities in animals to some extent. In fact, what sets humans apart from other species is not a single and exclusive aptitude. This is due to the complex mixture of cognitive (e.g., self-awareness), bodily (e.g., several facial expressions of emotion), and sociability (e.g., morality and respect) features that take humans beyond standard biological evolution and make them unparalleled in the world. In contrast to animals that are well developed for particular tasks (e.g., swing, search by smell, dash, and fly), humans are not specialized in such activities. However, we are well prepared to build and use artefacts to perform jobs (Melé & González Cantón, 2014). Moreover, humans are inherently social and well-evolved to transmit intent and knowledge to potential partners. So, human sociability was an outstanding ability to face the rough conditions of nature and gave them the upper hand over other species. Through social interactions, we successfully exchanged knowledge (about facts and artefacts), which flourished social learning and cumulative culture (Shilton et al., 2020). In a broad sense, culture can be described as shared characteristics and knowledge of a specific group of people that change as time goes on. Distin (2011) argues that human culture is the result of human nature and evolving information. In simple terms, information is the heart of human culture and society. As time went by, information technology has developed and let humans collect, restore and communicate a large amount of information and form new cultures and social structures.

### 2.2.2 Evolution of Human-Technology interactions

Information can bring to mean a myriad of things. More than 700 definitions for information have been found in the academic (Ibekwe-Sanjuan, 2012). This reveals that information is not a stand-alone concept. It depends on the receiving person who somehow makes sense of it and acts upon it in some way (Liebenau, 1990). In its general sense, information means any stimuli that have meaning for their recipient. Technological advances bore another fruit that enabled humans to communicate not only with each other but also with artefacts. A significant challenge in addressing CPHS is how technology is interpreted (Kant, 2016). Arthur (2009) indicates that technology can be: a means to reach a purpose, a set of practices and components, or a group of available devices and engineering practices. In simplified terms, the common definition of technology is the application of tools, processes, or techniques for practical aims.

Figure 4 depicts four technological evolutions within society. Preliminary technology refers to physical artefacts (e.g., hammers) built and used to perform physical actions.

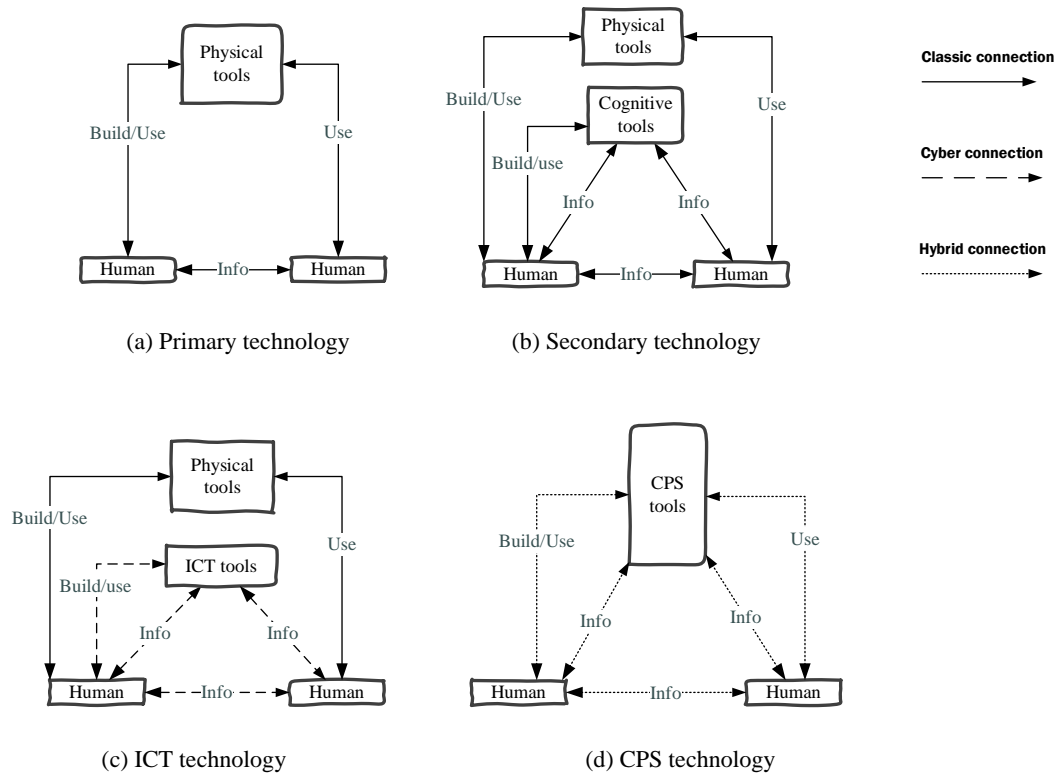


Figure 4 Technological evolutions within society

Secondary technology points out the development and usage of cognitive artefacts to reserve and communicate information (e.g., paper maps). The emergence of Information and Communication Technology (ICT) enabled us to access, store, transmit, understand and manipulate a tremendous amount of information remotely. Finally, CPS technology integrates cyber and physical tools to perform information processing and physical operations in parallel. The relationship between humans and artefacts has also changed along with the evolutions. Physical connection is the simplest form of connection that occurs between humans and physical artefacts. In cyber connection, physical contact turns to non-physical contact, whereas hybrid connections can include both physical and non-physical contact with artefacts.

### 2.2.3 Highlighted issues in human-technology interactions

CPHS highlights some issues regarding the interactions between humans and technology. Technology acceptance, Human-Centred Automation (HCA), as well as laws and ethics of technology are among the main underlined issues.

#### 2.2.3.1 Technology acceptance

The conditions under which people use technology within a human-centred system are remarkable. An important question associated with human-tech tool interactions is under



what circumstances people accept and use tech tools. This question is essential because people may not necessarily use all available systems, or their usage follows an evolutionary trend. Davis (1989) proposed the Technology Acceptance Model, which became the most widely known model of technology acceptance and usage. He suggests that perceived ease of use and perceived usefulness determine the behavioural intention of humans to use technology. This model has many criticisms because it cannot consider some factors, such as user characteristics (e.g., age) or social pressure, which could influence technology acceptance. Consider the example of educational technologies within the context of Covid. These technologies have neither been accepted because of training quality nor ease of use. They have been admitted by virtue of laws, social commitment, and responsibility. Venkatesh (2021) argues the importance of performance expectancy, effort expectancy, social influence, facilitating conditions, individual characteristics, technology characteristics, environmental characteristics, and interventions as prompting factors to accept technology and the use of tech tools. For example, adventurous and eager to learn, individuals are more expected to adopt tech tools. It should keep in mind that technology acceptance does not mean that humans must know how artificial tools make decisions and how they will behave in certain circumstances (Johnson, 2015). Trust in automation can be seen as a subclass of technology acceptance in CPHS that focuses on technologies that aim to automate sensing, decision making and action processes. Influencing factors in trust in automation can include reliability, validity, utility, robustness, and false-alarm rate (Hoffman et al., 2013).

### *2.23.2 CPHS automation level*

The automation in classic CPS is technology-centred, focusing only on increasing efficiency such that only technological constraints can limit the level of automation. For example, within inspection tasks that require judgment to assess quality in automobile final assembly lines, humans are preferred over CPS because artificial systems are not still fully able to evaluate quality from a human point of view (Groover, 2016).

Human-Centred Automation (HCA) is an alternative to technology-oriented automation and counteracts possible adverse effects on humans. The purpose of HCA is not necessarily to automate previously manual functions but rather to enhance user effectiveness and satisfaction (Ntuen & Park, 1996). Unlike technology-centred automation, which resigns passive roles to humans, humans can have dynamic (passive and active) roles in HCA. Dynamic automation (also called adaptive automation) is wide-spreading in CPHS and is defined as a form of automation that is flexible or dynamic in nature (Parasuraman & Mouloua, 2018). It occurs when the automation stage change between the human and tech tools during the system operation, depending on tasks and conditions (Trapsilawati et al., 2018). Dynamic automation raises the system's robustness during operations by the possibility of changing the level of automation. Ntuen and Park (1996) argue that in dynamic HCA, humans must be able to modify the automation level to fit their needs. Using dynamic automation, CPHSs are more

flexible and adapt to variable circumstances and expectations.

Let us have an example. A human pilot can set and use the autopilot system (Tech tools) to reduce the workload during long flights. This system can control the aircraft without the human pilot performing the controls. However, if the autopilot fails or cannot make decisions during the flight, it notifies the human pilot to take over the control of the aeroplane again. In this example, dynamic automation is manifested such that humans can ascribe a task to artificial systems and vice versa.

### *2.2.3.3 Laws, regulations, and ethics of technology*

Different laws and regulations may govern the interactions in CPHS. For example, the rules of inaccessibility may imply that tech tools should not directly influence the behaviour of humans (Haff, 2014), the rules of security may state that humans should not influence the behaviour of tech tools, and the regulations of control may define how humans should control tech tools. Recently, the ethical rules of technology are more highlighted. This rule refers to the use of ethical thinking to address the growing concerns about tech tools. Technology ethics may constrain information accessibility due to privacy and moral limitations or make the use of tech tools subject to certain conditions.

### **2.2.4 Socio-Technical nature of CPHS**

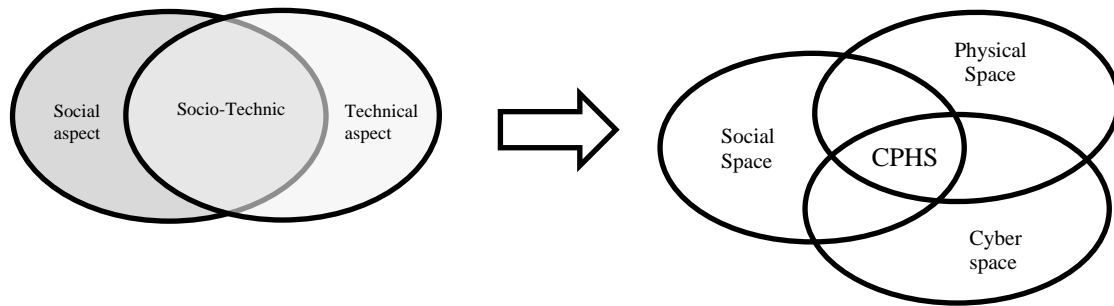
Until the middle of the twentieth century, prevalent ideas dictated that technology should be considered independent and humans (with the mental and social conditions) should follow the given technical structures. In the second half of the 20th century, mixed socially and technically constructed systems led to the birth of a new ecosystem called the "socio-technic."

The concept of the socio-technical environment emerged to emphasize the interrelationship between humans and technology to strengthen the technical and social conditions. STS consists of many technological artefacts (e.g., machines, vehicles, and phones) and social entities (e.g., individuals, governments, and organizations) (Van Dam et al., 2012), which connect each other through social, physical, and cyber connections.

We should highlight two points here. First, due to social and technical practice, STSs have neither fully deterministic nor completely non-deterministic behaviour (Savaget et al., 2019). The second point is that the social aspects of STS can affect the technological aspects and vice versa (Ropohl, 1999). For example, on one side, the involvement of education systems in the context of Covid promoted distance learning technologies; on the other side, these technologies raised unprecedented educational behaviours.

In STS, drawing a line between the social and technical systems is generally difficult and sometimes even impossible. Therefore, the joint performance of the technical and social subsystems should be considered to improve STS, which raises a need for a multidisciplinary approach.

Currently, hospitals, companies, homes, and other social environments are incrementally inundated with new technologies so that each technology represents a new function and provokes new social behaviour. As discussed in chapter 1, many studies have looked at CPHS as STS. So, we can conclude that CPHS is located in a dual space (i.e., social and technical). If we break down technical space into cyber and physical space, we will reach a triple space shown in Figure 5.



*Figure 5 Socio-technical space of CPHS*

This leads to a finding that CPHS can be affected by social, physical, and cyber events. The position of CPHS in this triple environment brings us the highest abstraction degree of the system. Due to the multi-dimensional nature of CPHS, the term environment in CPHS pertains to various meanings according to the context, which should not be confused with each other.

(1) Socio-technical environment means the co-existence of different hardware, software, and wetware (persons, organizations) aspects and their integration requirements.

(2) System environment determines the setting and circumstances of all influences upon a system (ISO, 42010:2011).

(3) Physical environment refers to the surrounding physical space where the physical tools (Kroes et al., 2006) or humans are placed.

(4) Ambient is an environment that people use as a tool, e.g., ambient intelligence (Kaptelinin & Nardi, 2018)

(5) Social environment includes society and all surroundings influenced by humans, e.g., relationships, communication, institutions, culture, and social rules.

(6) Cyber environment refers to where all digital phenomena (e.g., data storage) occur in the digital world.

STS intends to integrate the social objectives with the technical requirements to keep the system operable (Fox, 1995). Thus, we can say that the purpose is the main element of CPHS that shapes its structure and directs its behaviour.

## 2.2.5 Activity theory

Activity theory (AT) is a suitable theoretic foundation for analysing complex STS (Durst et al., 2020). This theory stresses a goal-directed approach by addressing technological, organizational, social, and human aspects. Since CPHS operates based on humans' expectations and their communities and enhances human-to-tool and human-to-human interactions (Dey et al., 2018), AT is an adequate lens for studying CPHS.

Activity theory (AT) was presented as a psychological framework for studying human sciences in the Soviet Union in 1920. After many years of development, AT became a well-liked theory and was adopted by professionals in various fields, making it an interdisciplinary approach. In this line, a large body of literature used AT to study Human-Computer Interactions (Clemmensen et al., 2016; Kaptelinin & Nardi, 2018; Kuutti, 1996; Nardi, 1996), information systems (Iyamu & Shaanika, 2019; Karanasios et al., 2018), human-technology interaction (Kaptelinin & Nardi, 2018), human-robot collaboration (Clodic et al., 2007) and computer supported cooperative work (Durst et al., 2020)

The notion of activity is the fundamental concept of AT. Kaptelinin and Nardi (2012) define an activity as a unit of behaviour that bridges the subject (actor) and the object (objective entity). Leont'ev (1978) held that the structure of activity could be shown through a hierarchical form. Albrechtsen et al. (2001) summarized this hierarchical form as shown in Table 7.

*Table 7. Three-level hierarchy of activity Source: Albrechtsen et al. (2001).*

Level	Directed at	Analysis
Activity	Motives	Why somethings take place
Action	Goals	What takes place
Operation	Conditions	How is it carried out

The levels of activity can happen simultaneously. As an example, remote tumour surgery can be perceived as an activity, so tumour removal is an action, and using robot arms can be seen as an operation. In general, activities refer to long-term functions and always have an essential purpose, while actions are short-term and try to reach their specific goal (Hasan, 2003). Activity, action, and operation can be transformed into each other if motives, goals, conditions, or context change (Bedny et al., 2014).

Person-centred, social-oriented, and network-based approaches are three consecutive evolutions that can be imagined for AT. The person-centred technic investigated the interaction between the subject, artifact, and object. Next after, AT was developed to look at the activities within a social context, and finally, network-based approaches were proposed to study a set of interconnected activities in an activity network. Social-oriented is the most famous approach in the literature. Engeström et al. (1990) introduced the "triangular" activity system model (see Figure 6) that has been broadly employed to formulate the relationships and interactions

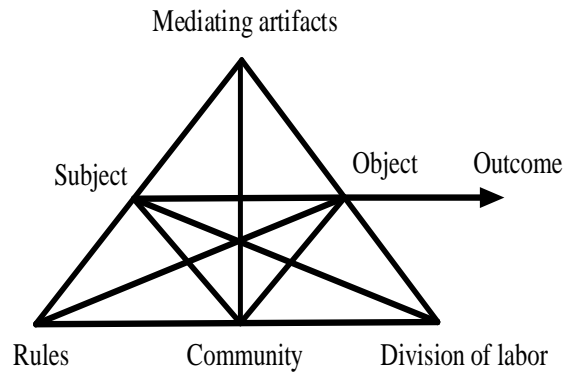


Figure 6 Triangular activity model presented by Engeström (1999).

between humans and technologies. This model uses seven principal concepts that should be considered on the whole because they are linked to the various aspects of activity (Clemmensen et al., 2016).

In the following, we review the concepts of AT and give short descriptions of the concepts.

- *Object*

An essential activity characteristic is object-orientedness, such that an objectless activity is meaningless (Leont'ev, 1978). The object is a concept to satisfy a need. It has sometimes been found that object and motive are used as synonymous terms, but it should stress that each activity may have several and even contradictory motives. In this regard, Kaptelinin and Nardi (2018) point out that the object should be not only a motivation but also a direction for activity. Moreover, it should be noted that it is the object that distinguishes between activities (Kuutti, 1996). The object can be changed (Engeström, 1999), but if these changes occur frequently, it can lead to activity disorder (Kaptelinin & Nardi, 2018). Therefore, if means and motives change, the object should be reviewed to guarantee the activity's effectiveness.

- *Subject*

The subject is represented by an individual or a group of people who have needs that motivate and direct them in the world; thus, a relation emerges between the object and the subject so that the subject finds his needs in reaching the object and, conversely, the object motivates and directs the subject.

- *Mediating artefacts*

Humans can construct and use tools to indirectly meet their needs. Vygotsky (2012) divided mediating artefacts into two groups: (1) Physical artefacts that are used to help the subject perform practical actions (e.g., hammer). (2) psychological artefacts (signs) are means utilized by the subject to fulfil mental action (e.g., maps and 3D models).

- *Community*

Activity generally is realized in a community (social environment) that comprises one or more individuals who play the roles in an activity system and share an object that shapes and directs actions (Igira & Gregory, 2009). The point of difference between community members and the subject may reside in the fact that if we remove the subject, the activity becomes

meaningless and cannot be conceived, but if a community member is eliminated, the activity may be done but not appropriately. If humans work together to reach a specified need, the concept of collective activity is shaped (Bedny et al., 2014). Engeström (1999) believes that the object of a collective activity should be defined by the community that carries it out.

- *Division of labour*

Division of labour is related to the structure of hierarchical activity and how to divide and distribute actions among members of society. Division of labour defines different roles and responsibilities for members of the community in an activity (Engeström, 2001).

- *Rules*

Engeström (1999) states that laws mediate the relationship between subject and community, subject and object, as well as object and community. They are related to explicit or implicit agreements about how the activity will be carried out to stabilize the system. (Kain & Wardle, 2014).

- *Outcome*

The outcome of an activity can be many and not always those anticipated or desired. Furthermore, outcomes provide a mechanism to evaluate the effectiveness of an activity.

- *Activity network*

When studying complex systems, using one activity model is often not adequate. Such systems need to be modelled as networks of activity. Activity theory has an efficient networking ability. An activity network can be established in three different ways:

(1) Using the outcomes of one activity to give rise to another one (Kaptelinin & Nardi, 2012), as illustrated in Figure 7.

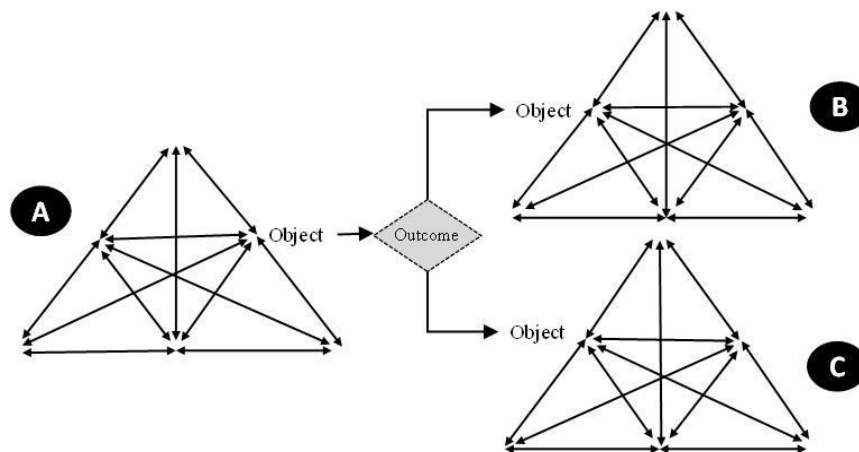


Figure 7 Network of activities- Conditional sequence.

(2) Coupling objects to make a new object (Anh & Marginson, 2010; Bakhurst, 2009; Engeström, 2001) as shown in Figure 8.

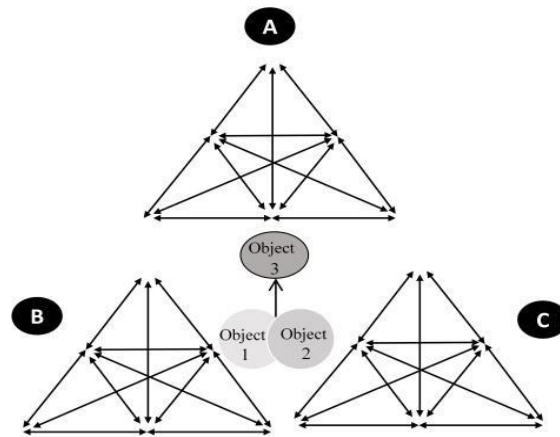


Figure 8 Network of activities- Integrating objects.

(3) Expanding the activities (neighbour activities) aimed at providing constituents of central activity (Hasan, 2003; Roos, 2012) as illustrated in Figure 9.

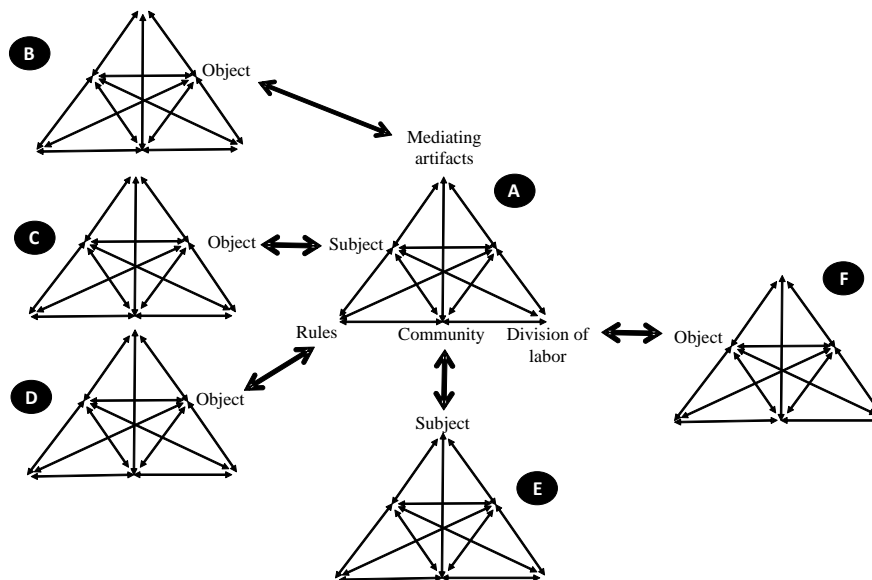


Figure 9 Network of activities- Neighbour expansion.

## 2.3 Modelling and Simulation (M&S)

Depending on the context, M&S can have different viewpoints. From a philosophical point of view, M&S is a way of thinking and reasoning about a system (Fishwick, 1996) and from a systemic standpoint, it represents a system at some level of abstraction that may illustrate and incorporate logical, mathematical, and structural aspects of the system (Carson, 2005). M&S is constituted of two different concepts. Modelling refers to the activity of model creation (Fitzgerald et al., 2014), while a simulation is related to the models that behave or operate like a given system when provided a set of controlled inputs (ISO/IEC/IEEE, 24765:2017). It should be emphasized that the level of detail in models depends substantially on requirements and needs.



Lee (2015) argues that models can follow deterministic and nondeterministic paradigms. A deterministic model has precisely one behaviour, and no randomness is involved in it. In contrast, unknown or unknowable properties are central in non-deterministic models. The combinations of deterministic models are not always deterministic models and can be represented as non-deterministic models.

Verification and Validation (V&V) is an inseparable part of any M&S to ensure that a model and the model's results are correct for specific use (Loper, 2015). V&V raises several issues resulting from multiple and heterogeneous models, multilayer architecture, and real-time approaches. Since models are expected to change and evolve over time, model synchronization may require real-time performance (Talkhestani et al., 2019). Model synchronization refers to the alignment of models with the real world in real or near-real time by dynamic modifications. The value of a model relies on its understandability, fidelity, and analytical capability (Lee, 2015).

Modularization is a helpful mechanism to reduce the complexity and enhance the flexibility of models (Talkhestani et al., 2019). The idea behind modularization is to divide a complex model into several smaller and less complex models that are as independent as possible. Hence, models should be designed in such a modular fashion that they become encapsulated and specify the boundaries and how models interact with each other.

There can be no denying that interaction among models is vital, and combining various models is often unavoidable. Since a new connection between the models may be required, and models are expected to be changed, replaced, or added, model interoperability (interchangeably with compatibility) would seem necessary as an ability to ensure that model is able to be matched and communicated correctly, synchronously, and effortlessly with other ones. Furthermore, it can overcome the difficulties of mastering distributed and heterogeneous models (Attiogbé, 2017). Accordingly, interoperability plays a vital role in the evolvability of M&S.

Modelling approach, modelling formalism and simulation technology are considered fundamental issues in M&S. Thus; in the following, we will review some of the most prominent ones in the literature.

### 2.3.1 Agent-based approach

The mechanisms of CPHS are to be flexible in responding to changing environments and highly dynamic variations. A large and very large CPHS has many components that perform critical system functions. In this frame, CPHS may use decentralized architectures, which decompose the overall system into smaller sub-systems with interactions and a degree of cooperative autonomy.

Agent technology provides a natural way to deal with distributed intelligent systems (Shen & Norrie, 1999). This technology has found its way into M&S. This approach in M&S



demonstrated its usability in modelling complex, cooperative, and adaptive distributed systems, which couple with autonomous, intelligent, and interacting entities characterized by different behaviours and goals (Fortino et al., 2016). The agent-based approach allows for modelling individual behaviour to obtain the system's overall behaviour (Postema & Haverkort, 2015). The definition of an agent is still controversial among scholars. Although different definitions of agent exist in the literature (Davidsson & Johansson, 2005; Ferber & Weiss, 1999; Luck et al., 2003; Macal & North, 2005; Weiss, 1999), in a general way, we can define an agent as a virtual autonomous entity located in a dynamic environment that can communicate with other agents according to protocols and is also able to perceive and act in order to achieve the goals for which it was designed. This entity has encapsulated characteristics that can be changed through its internal behaviour (actively) or external stimuli generated by other agents (passively). Postema and Haverkort (2015) define an agent-based simulation to be a discrete event simulation where agents interact with other agents within an environment.

The agent-based approach emphasizes the importance of learning (Schlesinger & Parisi, 2001), which is also a pivotal concept in the behaviour of humans and intelligent systems. Learning may be intended for self-reconfiguration, self-adaptation, and self-organization, to perform appropriate behaviour (Mele et al., 2010). Since learning is a context-dependent concept, we discuss human and machine learning from psychology and computer science perspectives.

### *2.3.1.1 Human learning*

A low percentage of our behaviour is instinctive, and most of them are learned. Human learning is known as a tool to acquire experiences, the results of which are reflected in one's permanent change in behaviour or in behavioural potentiality (Ormrod, 2016). We study human learning to understand why humans behave as they do. Many learning theories have been developed to explain human learning. We look into three key and most-used learning theories. These theories are categorized according to their ideas of how learning occurs.

One of the preliminary learning theories relies on methodological behaviourism. Behaviourists assert that we can study only the observable behaviours, and subjectively internal events like thinking and emotion are too difficult to assess, so they should be ignored (Powell et al., 2016). Behavioural Learning Theory believes that a person's environment determines behaviour. In other words, our responses to environmental stimuli shape our behaviours (Austin et al., 2001). Complex behaviour is presumed to involve extremely long chains of this response to stimuli (S-R) connections. The role of memory and motivation is not explicit in this theory because it does not study internal processes (Schunk, 2012).

Cognitivism, or cognitive learning, is a theory that takes into account internal conditions, and learning occurs not only by the S-R model but also by internal information processing. Cognitive learning puts stress on internal processes like attention, perception, short-term

(working) memory, long-term memory, and forgetting (Schunk, 2012).

Working memory capacity is a significant state variable that is known to have an influence on human learning. Work memory (also sometimes called short-term) is a mechanism for temporarily storing information (generally lost within 30 s), which is essential for cognitive capacities such as attention, reasoning, and learning (Spector et al., 2014). Long-term memory stores a deluge of information for a long time via procedural memory (implicit knowledge) and declarative memory (explicit knowledge) (Kotseruba & Tsotsos, 2020).

Latent learning is a kind of cognitive learning and believes that learning can occur without observable indication of learning and only can be seen under a different set of conditions (Powell et al., 2016). Wang and Hayden (2021) argue that curiosity can lead to potential learning, which becomes evident in a particular condition.

Although observing people's physical behaviours is not tricky, understanding the cognitive process of others is impossible through direct observation. Thus, all aspects of other people's minds must be inferred from available information and the behaviour that people manifest. Mind theory allows individuals to attribute thoughts, desires, and intentions to persons in order to predict and explain their behaviours (Williams, 2012).

Another theory is social learning (theory of observational learning), which believes that studying behaviour alone couldn't give us a comprehensive view of learning (Ormrod, 2016).

Individuals often look beyond their own experiences to consider the experiences of others in their immediate social networks. Therefore, social learning emphasizes observing others' behaviour as a lever of learning and a determinant of behaviour change (Olson, 2015).

### *2.3.1.2 Machine learning*

Machine learning is a part of artificial intelligence (Alpaydin, 2020). Many applications and methods can be conceived for machine learning. Here, we argue the most commonly known machine learning mechanisms. The first type is supervised learning which aims to learn by training data (labelled datasets) that helps to learn patterns to classify data or predict outcomes (Banerjee et al., 2018). Unsupervised refers to the methods in which we like to find a pattern in input data (unlabelled datasets) such that it occurs more often than others (Alpaydin, 2020). Reinforced learning differs from supervised and unsupervised learning. Reinforcement learning uses the ideas from dynamical systems theory and lays stress on learning by an agent through trial-and-error interaction with its environment in terms of states, actions, and rewards without requiring complete predefined data (labelled or unlabelled) (Sutton & Barto, 2018). Among machine learning methods, reinforcement learning seems to manifest human learning more appropriately (Ghanipoor Machiani & Abbas, 2016).

As discussed in 1.4.1, real-world interaction is crucial for social robots. In this regard, reinforcement learning has been properly applied to develop social robots. These robots should be capable of adapting their behaviours according to the changing needs and feedback of the user (Nocentini et al., 2019). Akalin and Loutfi (2021) conducted a survey on reinforcement

learning approaches employed in the social robot learning process.

### 2.3.1.3 *Humans as agents*

Humans can be present in a system in different forms. They can use real systems, employ simulated systems or be a part of a simulated environment (people and systems) (Mittal & Tolk, 2019). Here, we review the last one, where people should be developed as models.

Human modelling is an area that raises significant differences between CPS and CPHS modelling. People do not always act in a deterministic manner. They may show nondeterministic behaviour depending on the situation (Gateau et al., 2016). In this vein, humans are typically modelled as autonomous and intelligent entities that can express various behaviours. Understanding and predicting humans' behavioural, psychological, and physiological aspects require complex M&S techniques (Nunes et al., 2015; Royston, 2016). M&S of human behaviour can become even more challenging when there is a need to model a group of people, a so-called simulation of crowd behaviour (Folds, 2015; Luo et al., 2009; Sycara & Lewis, 2008). Human multitasking modelling is another challenge when we model humans dealing with doing several things at once (Human multitasking) (Pew & Mavor, 1998). This is why few researchers have tended to incorporate human models for the M&S of a system and often have tried to oversimplify them for specific simulation purposes. Given the individual differences of humans, human digital models should be able to represent the generalities and similarities of humans' abilities and behaviours and take into account their individual differences.

In order to build a human digital model properly, several support models may be needed (e.g., models of human error, state inference, perception, human decision, and learning). The basic idea of the digital human model is to provide high behavioural fidelity to the extent to which it satisfies the requirements of M&S. Behavioural fidelity plays a substantial role in the validity of M&S (Pace, 2000). Behavioural fidelity indicates how well human behaviour that occurs in simulation is consistent with human behaviour in the real system (Folds, 2015).

From the standpoint of model implementation, behaviour models should be made so that other models can work with them. Luo et al. (2009) argue that human behaviour models should consider four issues indicated in psychology studies.

- A person's experiences can affect a person's behaviour rather than some complex decision rules.
- As intrinsic states of a person, the influence of emotions cannot be overlooked in a person's behaviour.
- The process of decision-making and action should be seen as multiple layers of macro-level/microlevel interactions.
- The behaviour of an individual may become distinct when she/he is in a social group.

The Belief-Desires-Intention (BDI) is one of the most popular architectures for high-level model intentional decision-making of human agents (Balke & Gilbert, 2014). This architecture has been used to model human-like characters in simulated environments (Adam & Gaudou, 2016). In this context, beliefs refer to the agents' knowledge about their surrounding world. Belief is used instead of knowledge because an agent's beliefs may not necessarily be true. Desires are the agents' goals, and the motivational state and intentions represent what the agent chooses to do in order to achieve its goals (Adam & Gaudou, 2016). The architecture of BDI architecture is illustrated in Figure 10. The events can be described as triggers that may update beliefs, select plans, and modify goals.

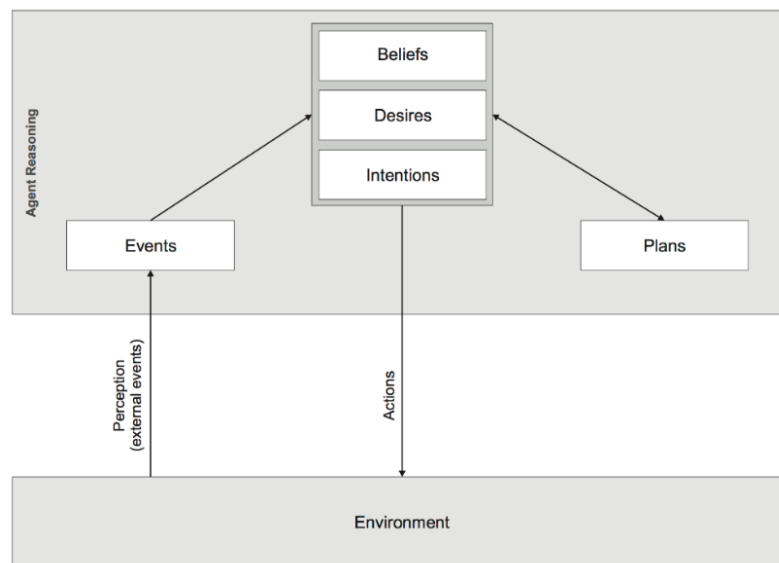


Figure 10 BDI architecture. Source: (Balke & Gilbert, 2014)

One of the criticisms of the BDI mechanism is the lack of learning behaviour (Phung et al., 2005) and emotions (Jiang & Vidal, 2006). In this regard, Guerra-Hernández et al. (2004) discuss BDI learning agents which have learning capacity behind their behaviours. Personality and emotion have a general influence on human agent behaviour. Several studies have been dedicated to modelling agents with personality and emotions. Personality reflects the tendency to show a particular reaction or behaviour under certain circumstances.

Ahrndt et al. (2015) argued that personality undoubtedly affects all relevant phases of the decision-making process. Accordingly, they made an effort to integrate the characteristics of the personality into the life-cycle of BDI for behavioural modelling. Big Five personality traits, also called OCEAN (Openness, conscientiousness, extraversion, agreeableness, Negative emotionality), is an accepted personality model by psychologists that is largely used in M&S. Ghasem-Aghaee and Ören (2007) have developed agents with a personality to study the influence of personality type to decision-making and problem-solving processes. To do so, they used the Big Five personality traits to model agents' personalities. A multi-agent simulation system has been developed by Canuto et al. (2006), in which the personality is

implemented in the internal functioning of the agents using Millon's personality theory, which is an extension of the Big Five theory.

Jones et al. (2009) proposed an extension of BDI architecture to consider physiology, emotion, and personality in crisis situations. Zoumpoulaki et al. (2010) used the OCEAN model of personality and the Ortony, Clore & Collins (OCC) model of emotions in BDI architecture to make a simulation model of emergency building evacuation. OCC is an interesting model of emotions among computer scientists who tend to build artificial characters that reason about emotions or incorporate emotions (Steunebrink et al., 2009). It can be called a semi-formal description language containing twenty-two emotion types that are grouped into six classes (Adam et al., 2009).

Jiang (2008) underlines that how emotions are presented, how they affect the decision-making process, and how emotions are updated are three key issues that need to be addressed in order to incorporate emotions into agents. Jiang et al. (2007) considered primary and secondary emotion within BDI architecture and introduced a generic architecture for an emotional agent called EBDI. Puica and Florea (2013) have used BDI architecture and proposed an emotional architecture to improve human agent performance.

A generic model for describing and updating the parameters related to human emotional behaviours has been proposed by Egges et al. (2003). In their proposed model, they tried to define a personality model and find its relation with the personality model used in OCC.

OCC is an interesting model of emotions among computer scientists who tend to build artificial characters that reason about emotions or incorporate emotions (Steunebrink et al., 2009).

### 2.3.2 High-Level Language for Systems Specification (HiLLS)

Typically, discrete-event models are utilized as the most intuitive models to grasp all forms of dynamic models (Zeigler et al., 2018). Discrete-event approach has been used to model both human (Bouanan et al., 2016; Seck et al., 2004; Seck et al., 2007) and CPS behaviours (Chi & Lee, 2001; Yue et al., 2010). The Discrete Event System Specification (DEVS) formalism was provided as a common basis for discrete-event M&S (Vangheluwe, 2001). DEVS is deemed to not only model behaviour but also model structure in its formalism (Diouf et al., 2022). A system modelled with DEVS is based on modular and hierarchical sub-models, which can be either behavioural (Atomic) or structural (Coupled) (Marcosig et al., 2018).

An atomic model is depicted as  $A = \langle X, Y, S, \delta_{int}, \delta_{con}, \delta_{ext}, \lambda, t_a \rangle$

Where:

- S is the set of internal states. A state is a list of values that are essential to define the status of the system at any moment.
- X is the set of input events

- $Y$  is the set of output events  
(Event is an instantaneous occurrence that can be received or sent via input and output ports)
- $ta$  is the time advance function to specify the lifetime of a state  
( $ta: S \rightarrow \mathbb{R}^+$ )
- $\delta_{int}$  is internal transition function ( $\delta_{int}: S \rightarrow S$ )  $s \in S$ . It specifies how the system changes state when lifetime of a given state is elapsed
- $\delta_{ext}$  is external transition function ( $\delta_{ext}: S \rightarrow S$ ). It specifies how the system changes state when an input is received.
- $\delta_{con}$  is confluent transition function ( $\delta_{con}: S \rightarrow S$ ). It specifies how the system changes state when the lifetime of a given state is elapsed and input is received simultaneously.
- $\lambda(s)$  is the output function  $\lambda(s): S \rightarrow Y$

As the coupling of one or more Atomic DEVS', a Coupled Model (CM) of DEVS is defined:

$$CM = \langle X_{self}, Y_{self}, \{M_d\}_{d \in D}, \{I_d\}_{d \in D}, \{Z_{i,j}\}_{i \in D \cup self, j \in I_i} \rangle$$

Where:

- $X_{self}$  and  $Y_{self}$  are equivalent to the  $X$  and  $Y$  in atomic models (Self denotes the coupled model itself)
- $\{M_d\}_{d \in D}$  refers to a set of components where each of them must be an atomic DEVS.  $M_d = \langle X, Y, S, \delta_{int}, \delta_{con}, \delta_{ext}, \lambda, ta \rangle$
- $\{I_d\}_{d \in D}$  denotes the influence set of component model  $d$  i.e., all other models sending input to  $d$
- $Z_{i,j}$  is the output-to-input translation functions including  $Z_{self,j}: X_{self} \rightarrow X_j$ ,  $Z_{i,self}: Y_i \rightarrow Y_{self}$ ,  $\{Z_{i,j}\}: Y_i \rightarrow X_j$

Bouanan et al. (2016) used the agent-based approach and DEVS formalism to study social influence through M&S. They modelled individuals and groups of individuals as agents possessing a set of attributes (e.g., gender, age, and languages), variables (e.g., opinion, satisfaction degrees, and interests), and behavioural functions. DEVS formalism has also been applied to CPS modelling (Ahmad & Sarjoughian, 2020) and IoT Management Systems (Albataineh & Jarrah, 2019).

On the one side, using DEVS mathematical representation is confusing for modelling large and complex systems; on the other side, implementation of models in software requires a graphical modelling approach to facilitate understanding the structure and the behaviour of large systems and develop simulation models. HiLLS is a high-level graphical modelling language composed of concepts from DEVS and software engineering using concrete notations to spell out the structure and behaviour of models (Aliyu et al., 2016). This graphical language

federates UML, DEVS, and Formal Methods (FM) to promote Model-Driven Engineering (MDE) techniques with the purpose of complex systems modelling (Samuel et al., 2019).

HiLLS enables modellers to define agents in the form of H-Entity, i.e., H-System and Hclass agent. Hentities can be connected to each other by the UML notations (inheritance and composition relations). This allows modellers to break down the complex model into several smaller and less complex models that are as independent as possible. H-System comprises variables, operations, and Phase Transition Diagram (PTD). Figure 11 illustrates the structures of the H-System and H-Entity of HiLLS.

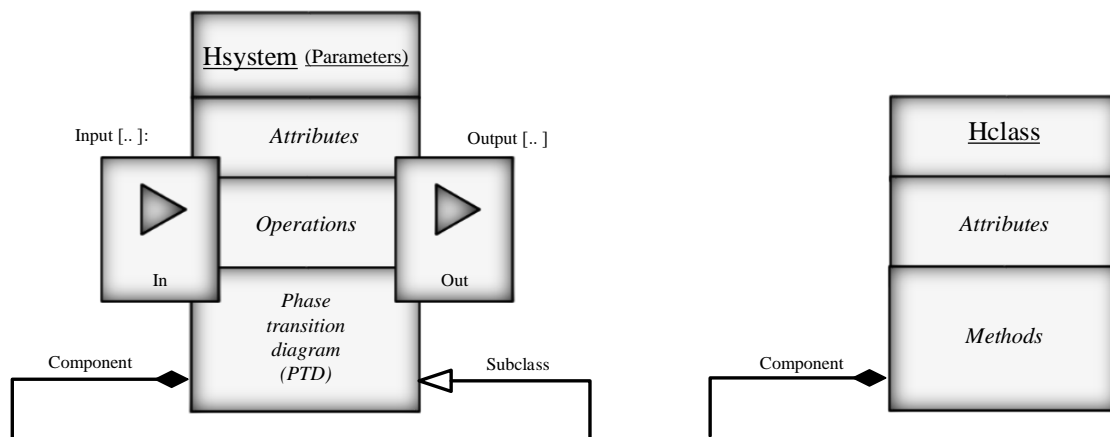


Figure 11 The structure of HiLLS's blocks

An H-System can include other H-Systems coupled together. This, enable us to build nested H-Systems. Two boxes at the left and the right of the H-system denote input and output channels (or ports) to exchange agents (Hentities) or information with its environment. In other words, the ports connect H-Systems to each other and the environment through the specification of message flows (called events). Operations are functions that can be called within transitions or states to manipulate the system's attributes and parameters.

A phase is a set of states that meet some conditions (Samuel et al., 2019). Phases are classified into finite ( $T = t$ ), infinite ( $T = \infty$ ), and transient ( $T = 0$ ) phases.

PTD shows the behaviour of the H-System, and the transitions between phases follow the rules of DEVS. However, the main difference is that, unlike DEVS, coupling and atomic models in HiLLS can be represented in the same way. Figure 12 shows the latest available concrete notations of HiLLS' phases and transitions. Activities of phases include the actions which should be executed when the intended phase is activated. Duration of life represents the amount of time a phase remains unchanged until a scheduled transition occurs. When a transition is triggered, it may check the conditions, send output to the ports or/and execute actions. To increase the readability of connections, conditional transitions can be represented in a compact mode.



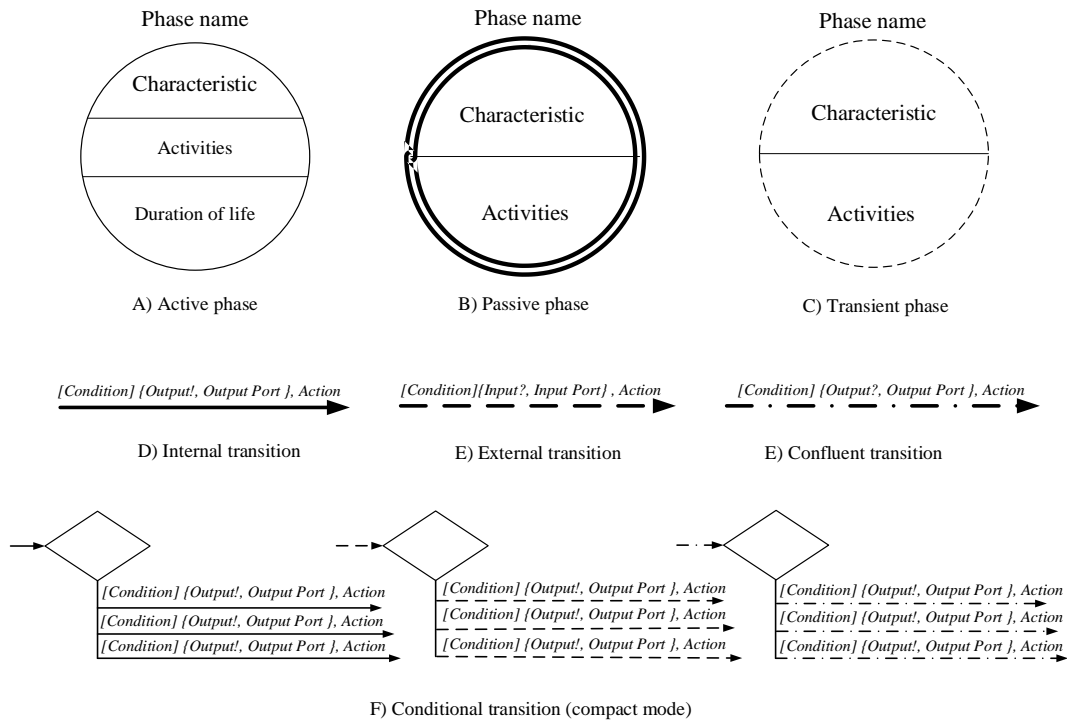


Figure 12 Concrete syntax of HiLLS

### 2.3.3 AnyLogic software

AnyLogic describes itself as multiple-method simulation software that supports process-oriented (discrete event), agent-based, and system dynamics simulation. This feature provides a high level of flexibility, enabling modellers to model almost all the behavioural aspects of complex and unique industrial, social and economic systems. Moreover, it provides a powerful experimental framework with extensive features for data analysis with an adequate level of accuracy that allows modellers to evaluate the results.

Although this software uses the language of graphical modelling, the models can be developed by Java code, which is one of the ideal languages for modellers. Thus, some parts of the source code can be written directly in Java and then imported into the application. A model developed in AnyLogic is fully mapped into Java code and, having been linked with the AnyLogic simulation engine (also written in Java) and, optionally, with a Java optimizer, becomes an entirely independent standalone Java application. This makes AnyLogic models cross-platform and can be run on any Java-enabled environment. Java is a high-level programming language that has a significant ability to create platform-independent applications. Object-Oriented Programming (OOP) has been created of the need to develop complex programs in a systematic, modular approach. The OOP approach allows programmers to build modules that can be used repeatedly in a variety of programs. These modules group related data and instructions for performing actions on that data. These modules encapsulate data to hide implementation details, are versatile enough to be extended through inheritance,



and give the programmer options through polymorphism. Encapsulation, inheritance, and polymorphism are features of every object-oriented language, including Java. Furthermore, the Java language can create platform-independent applications, meaning they can be run on any computer regardless of the operating system or hardware configuration.

Anylogic is a powerful tool for implementing HiLLS models. The agent-based approach in Anylogic allows modellers to develop and join heterogeneous models through communication links. Koïta et al. (2022) used AnyLogic to implement the HiLLS model for the evaluation of attack and defence strategies in CPPS. To this end, they provided simulation semantics of the HiLLS into AnyLogic using transformation rules, as shown in Table 8.

*Table 8 HiLLS to Anylogic transformation (Koïta et al.,2022)*

<b>HiLLS</b>	<b>ANYLOGIC</b>
H-System	Agent with port
H-Class	Agent without port
Attribute	Agent's variable
Parameter	Agent's parameter
Method	Agent's function
Operation	Agent's function
Input port	Agent's receiving port
Output port	Agent's sending port
Finite configuration	Agent's state with a delayed transition
Transient configuration	Agent's state with a zero delay
Passive configuration	Agent's state without delayed transition
External transition	Transition on receipt of a message
Internal transition	Transition with associated delay
Confluent transition	Transition with delay and condition
Composite H-System	Agent population
H-Systems interaction	The communication link between agents

## 2.4 Conclusion

This chapter addressed the socio-technical groundwork for CPHS and related M&S issues. To move forward, we gave a short presentation on human features and stressed that it is not just one characteristic that differentiates humans from other species or artefacts but a complex mixture of cognitive, bodily, and sociability features. Then, we explored the evolutions of human-technology interactions and discussed their evolutions. Then we investigated technology acceptance, human-centred automation, and ethics of technology as highlighted issues in human-technology interaction. As CPS technology and humans become entangled in CPHS, CPHS is shaped as an intelligent system with a socio-technical nature. So, we studied

CPHS from socio-technical perspectives and reviewed the activity theory as a salient theoretical foundation for studying STSs.

Our reviews were continued by looking into modelling and simulation. We reflected on the modelling approach, modelling formalism and simulation technology as fundamental issues in M&S. In this regard, we studied agent-based technology, which models a system as a collection of autonomous entities (agents). The agent-based approach emphasizes the importance of learning. So, we investigated various types of learning for humans (i.e., behavioural learning, cognitive learning, reinforcement learning, and social learning) and artefacts (i.e., supervised, semi-supervised, and non-supervised learning) that contribute to shaping the behaviours of agents.

Given the importance of human models in CPHS, we tackled agent-based human modelling. We underlined that emotions, learning, personality, context awareness, and situational awareness might influence their behaviours. Accordingly, the human behavioural model should consider these elements to provide high behaviour fidelity. HiLLS was investigated as high-level graphical modelling that can spell out the structure of agent-based models. This graphical model language takes advantage of UML and DEVS formalism to make platform-independent models. Finally, AnyLogic was presented as a powerful simulator software for implementing HiLLS Models.

With sufficient knowledge about the CPHS ecosystem and potential methods and techniques to model and simulate such a system, we can now develop our framework based on existing knowledge.

## Chapter 3

# Three-Layer Framework for Modelling and Simulation of CPHS

### 3.1 Introduction

As mentioned in the introduction, to answer research questions, we use a three-layered methodological framework with a multidisciplinary approach (See Figure 1). The present chapter reveals the layers of the framework. As the first layer, the PCL is argued in section 3.2. BCL is the second layer that will be introduced in section 3.3. Finally, in section 3.4, ECL will be discussed as the third layer.

### 3.2 Purpose-Centric Layer (PCL)

PCL can be conceived as a teleological architecture. It is useful to reflect on what we mean by the two key terms "Teleology" and "Architecture.". The word "Teleology" is derived from the combination of the Greek "Telos" (purpose) and "Logia" (study of), which refers to the study of the purpose of something in the world. Architecture refers to a set of rules, guidelines, and recommendations to explain what and how a phenomenon happens at a large scale and in complex environments. Accordingly, the teleological architecture denotes organized guidelines and recommendations to explore the CPHS ecosystem and explain how the system reaches its purpose through interactions. To this end, the architecture breaks down the CPHS

into more readily understood and structural concepts, focuses on utilitarianism and illustrates what end is to be achieved in its socio-technical environment.

To plausibly answer the first research question, we start by addressing the purposefulness and behaviour of CPHS. Then, we federate all necessary descriptive concepts into GPCM that can draw out familiar diagrams for modellers.

### 3.2.1 Purposefulness

Understanding the purpose is key to interpreting a system. CPHS, like all man-made systems, is designed for a variety of reasons. We consider the purpose of CPHS to be the reason for being. In systems thinking, the system goal depends on the viewpoint of the observer. In other words, from different angles, the purpose of a system may seem dissimilar. Thus, this is somehow unreal to describe a unified purpose for a large and very large CPHS in which numerous contributors with different standpoints may get involved.

Unlike CPS, which may be a human-centred system or not, CPHS is always a human-centred system such that it can provide information, knowledge, and physical assistance to satisfy human needs. In other words, CPS tends to achieve a full degree of automation, while CPHS does not. Every action within a CPHS must be somehow human-beneficial and tend towards the maximum degree of usability, which is the primary CPHS purpose. Usability means that the system should meet its purpose with effectiveness, efficiency, and satisfaction (ISO, 9241-210:2010).

We believe that any CPHS should pay particular attention to the three interconnected principles to be able to make a high level of usability. These principles form our standpoint on CPHS.

1) Pragmatism: One of the main differences between CPS and CPHS is the shift of focus from a technology-driven to a human-centric approach. CPHS should be designed and developed based on their beneficence to humans. Pragmatism points to the fact that the system should effectively meet human direct and indirect needs.

2) Humanism: People have special characteristics, i.e., the ability to accomplish a task (e.g., cognitive and physical), interests (e.g., motivation and preferences), and differences and relations (e.g., individual differences and social behaviour) that seek particular attention in the system. Taking human features into account not only increases human satisfaction but also improves the system's efficiency.

3) Instrumentalism: In CPHS, technology must be flexible enough to support various socio-technical needs and adapt to human behaviours. In this regard, tech tools should be developed to interact appropriately (with an adequate level of intelligence) with the people who accept using them. Establishing appropriate interaction requires consideration of the previous two principles (Nocentini et al., 2019).

To achieve the purpose appropriately, people may get involved in different system stages. In the case of all man-made systems, human beings can be viewed as users or system elements (ISO15288, 2015). In this way, people may contribute to CPHS as an actor to ensure the system's functionality (operation phase) or engage in the system as user(s) (utilization phase). To achieve high efficiency and satisfaction during the operation and utilization phases, we should know how CPHS behaves to accomplish its purpose.

### 3.2.2 CPHS behaviour

Dugdale (2013) argues that studying the interactions of components and how they influence overall system behaviours is vital for understanding any Socio-Technical System (STS). The general behaviour of CPHS is formed by interactions between components (tech tools and social entities). In simple terms, CPHS behaviour is shaped when the individual behaviours of components become coupled. In this way, Cao et al. (2011) define coupled behaviours as actions of actors who are associated with each other through certain relationships. Figure 13 shows an example of CPHS behaviour, consisting of two social (An individual, a group or an organization) and two tech tools that interact to meet a purpose defined by one of the social entities.

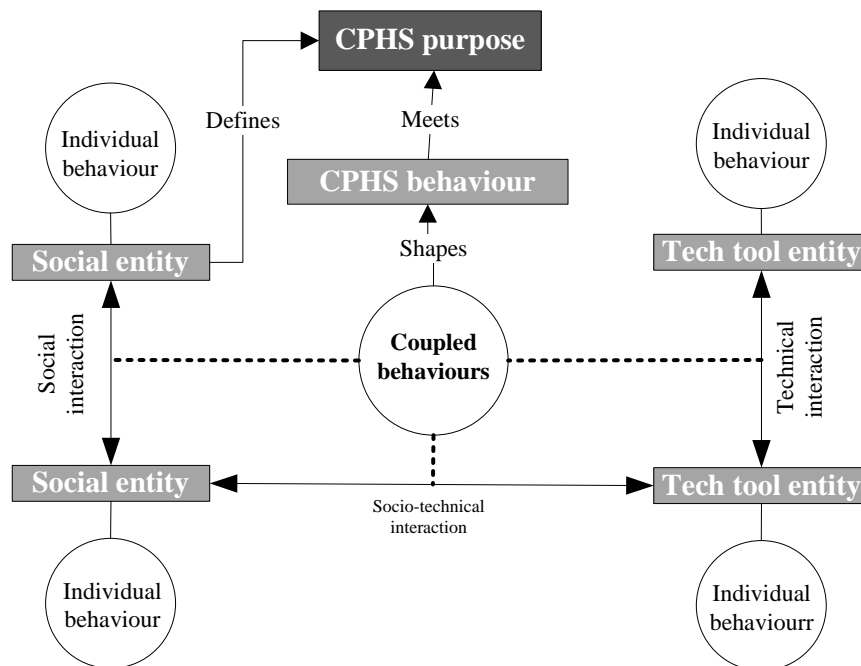


Figure 13 CPHS behaviour

As shown in the Figure 13, a coupled behaviour is shaped via interaction. An interaction is used to refer to the explicit action taken by an element (e.g., cyber, physics and human) that may have some effects or impacts on another element (Loper, 2015). If we take a closer look at the coupled behaviour of humans and tech tools, we realize that tech tools can influence human behaviour by providing information or physical services. In return, the behaviour of

tech tools can be generally affected by objectives and information provided by humans.

Figure 14 depicts all possible interactions that may occur inside CPHS. Human-System Interaction (HSI) is shaped once humans interact with a fully automated CPS. Human-Cyber system Interaction (HCI) refers to the actions related to exchanging information between humans and computational and virtual systems. This interaction includes human interactions with computers and also new technologies such as virtual reality, augmented reality, and Digital Twin. Human-Physical system Interaction (HPI) hints at the interactions between humans and physical artefacts (e.g., Human-Machin interaction). Human-Human Interaction (HHI) (also called social interaction) occurs between individuals to perform a task within the system (e.g., group decision-making and co-operations). It must be borne in mind that HHI can be established directly or via intermediary tools (Stefanov et al., 2009). The interactions between two cyber systems are established via Cyber-Cyber Interactions (CCI), usually related to digital data communications, whereas the interactions between physical systems (PPI) result in exchanging of mechanical energy. Another kind of interaction that can appear in CPHS is called Cyber-Physical Interactions (CPI), which enable cyber systems to monitor or control physical systems.

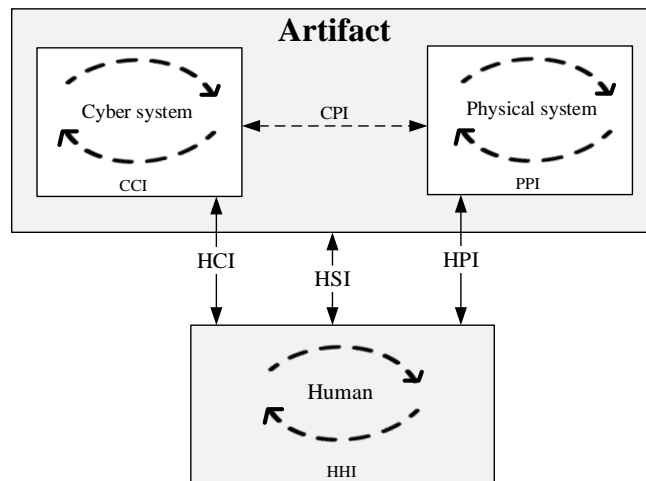


Figure 14 Interactions in CPHS

Discussed interactions allow CPHS to make mutual impacts between its components and form a chain of actions. Table 9 shows six patterns that can be considered for interactions between humans and artificial systems in CPHS. It should be pointed out that a single tech tool in the form of CPS can act as both cyber and physical systems simultaneously.

CPHS is among the intelligent systems. CPHS intelligence is the ability to determine how the system manages coupled behaviours to move toward its purpose. Table 10 presents different intelligence structures that exist for CPHS. Heterogeneous distributed intelligence seems to be a pervasive structure in CPHS (at least in the reviewed applications), where social and technological components construct collaborative intelligence.

Table 9. Interaction patterns associated with humans and tech tools in CPHS

	Pattern	Example
1	Cyber system → Human → Physical system	<i>Smart glass provides information to the operator who uses a machine to make a physical action.</i>
2	Cyber system → Physical system → Human (CPS → Human)	<i>Computer conducts a connected machine to deliver raw materials to the operator.</i>
3	Human → Cyber system → Physical system (Human → CPS)	<i>An operator uses a tablet to analyse real-time data and send the commands to a connected machine in order to carry out a physical action</i>
4	Human → Physical system → Cyber system (Human → CPS)	<i>An operator uses a machine that is monitored by a computer</i>
5	Physical system → Cyber system → Human (CPS → Human)	<i>A machine takes a physical action, and a computer shows the result to the operator.</i>
6	Physical system → Human → Cyber system	<i>A machine performs physical action, and the operator reports the results to a server.</i>

Table 10. Different structures of CPHS intelligence.

Overall CPHS intelligence structure		Description	Human position	CPHS example	Human potential roles
Distributed	Homogeneous	<i>Autonomous tech tools shape the system intelligence</i>	<i>Human-out-of-the-Loop</i>	<i>Autonomous bus fleet</i>	<i>Sensed item, Sensor carrier, Data provider, User</i>
	Heterogeneous	<i>Humans and tech tools form a collective intelligence</i>	<i>Human-in-the-loop</i>	<i>Intelligent production systems</i>	<i>Sensor carrier, Data/information provider, Sensed item, Decision-maker, Actor, User</i>
Centralized	Human-centred	<i>Human intelligence conducts the system</i>	<i>Human-in-the-loop</i>	<i>Telesurgery</i>	<i>Sensor carrier, Data/information provider, Sensed item, Decision-maker, Actor, User</i>
	AI-based	<i>A central AI directs all the system</i>	<i>Human-out-of-the-Loop</i>	<i>Intelligent traffic control system</i>	<i>Sensed item, Sensor carrier, Data provider, User</i>

### 3.2.3 Proposed Generic Purpose-Centric model (GPCM)

As already mentioned in chapter 2, AT is a suitable theoretical foundation for analysing complex STS (Durst et al., 2020). This theory stresses a purposive approach by addressing technological, organizational, social, and human aspects. Since CPHS operates based on the expectations of humans and their communities and also enhances human-to-tool interactions (Dey et al., 2018), AT is a proper lens for studying CPHS.

As discussed earlier in 3.2.1, human needs always direct CPHS (pragmatism). Similarly, according to the activity theory, an activity is conducted by its user(s) in a socio-technical environment to reach the object that satisfies needs. The activity architecture is the holistic representation of all involved actors and mediators to realize the purpose (Durst et al., 2020). The role of new technologies raises new challenges to existing activity architecture (Allen et al., 2011). Furthermore, AT is developed from the social sciences and psychology, which is why most of its descriptions and interpretations in engineering are vague or have different meanings. In this regard, it is necessary to adapt classical architecture to activities where artifacts are not just passive tools and then to translate concepts into engineering language so that architecture becomes intelligible and useable for modellers.

#### 3.2.3.1 Adapting AT architecture with the CPHS ecosystem

We modernize the classic activity architecture to answer new technological requirements. In the context of the proposed architecture for CPHS, the subject of the activity is the final user(s) who employ the CPHS to meet a purpose, e.g., clients in CPPS, help-seekers in IEMS, passengers in ITS, and patients in MCPS. In other words, users are those social entities (e.g., individuals, groups, or companies) that contribute to the utilization phase of CPHS.

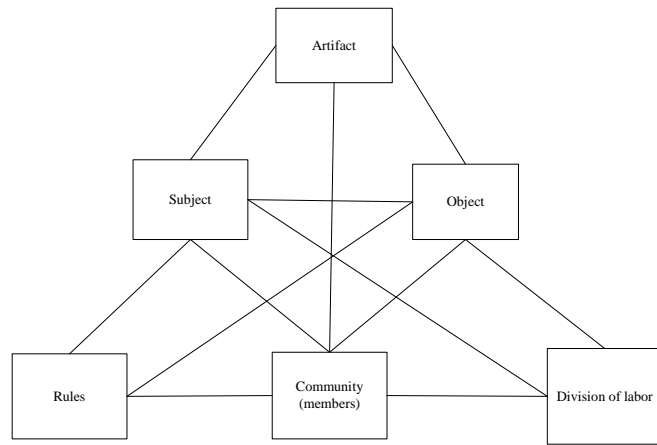
A community member is a social entity defined as a CPHS operator who provides certain functionalities to promote overall system operability (Kant, 2016). Put another way; the community members are those social entities involved in the operation phase.

In the classic AT, division of labour defines different roles and responsibilities for subject and community members in an activity. In CPHS, not only subject (user) and community members but also tech tools can take the roles in an autonomous and semi-autonomous way. Based thereon, the division of labour in classic AT became "Organizing" in CPHS because it should also deal with dynamic human-centred automation. For this reason, the organizing allocates the roles of the users, operators, and tech tools in the system to achieve the purpose according to the related rules and harmonious synergy between human characteristics and technological capacities. In other words, organizing is responsible for managing coupled behaviours in CPHS to satisfy the system's purpose.

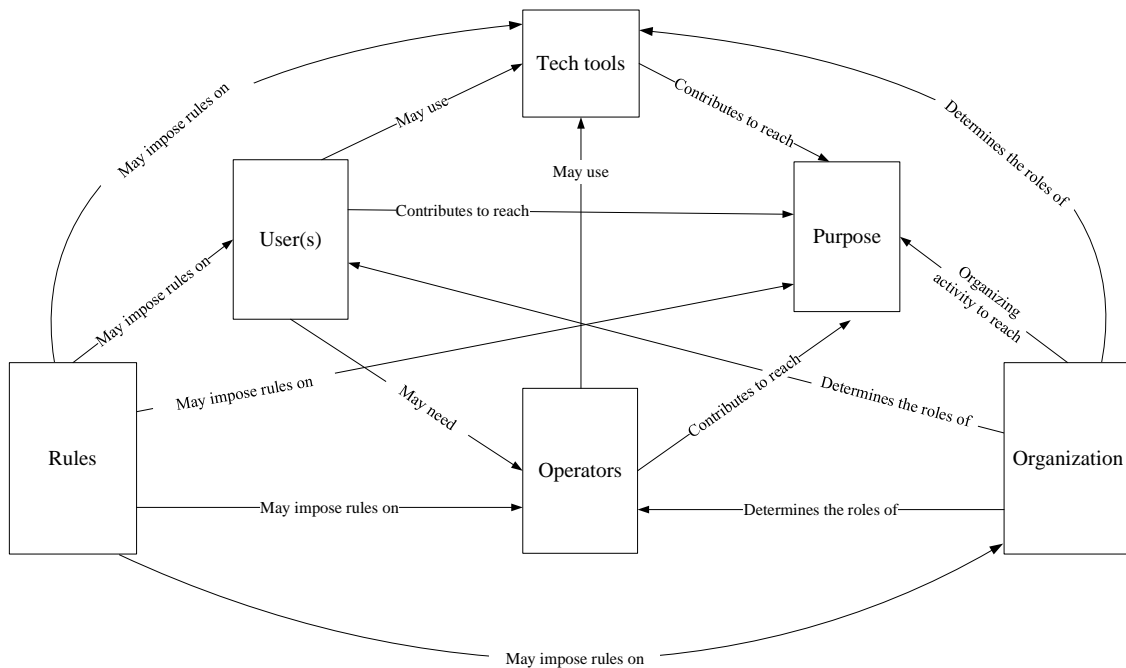
Three new relationships are established in CPHS activity architecture that did not exist before. They link rules, tech tools, and organizing. The relation between the rules and tech tools points out the laws (e.g., technical and safety regulations) that can regulate the behaviour



of tech tools. In CPHS, particular restrictions can be regarded for automation and task allocation to achieve the purpose. The relation between the rules and the organization denotes that ethical, social, or technical regulations can impose restrictions on operations and how they are allocated to humans or tech tools. The classic architecture and the proposed one are illustrated in Figure 15.



(a) Classic activity frame



(b) Proposed teleological architecture for CPHS

Figure 15 Classic AT frame vs. Proposed AT architecture for CPHS

First-order logic (FOL) is symbolized reasoning to represent knowledge in a logical form. We use FOL and set theory symbols to denote the knowledge of architecture as follows:  
 $GPCM = \langle R_l, U, P, O_p, O_r, T, R \rangle$  (Eq. 4-2-1)  
 With

$R_1$  is the set of rules

$U$  is the set of users

$P$  is the purpose

$O_p$  is the set of operators

$O_r$  is the organizing

$T$  is the set of tech tools

$R$  is the set of relations

$$R = R^{R_1-U}, R^{R_1-T}, R^{R_1-O_p}, R^{R_1-O_r}, R^{R_1-P}, R^{U-T}, R^{U-O_p}, R^{U-P}, R^{O_p-T}, R^{O_p-P}, R^{T-P}, R^{O_r-T}, R^{O_r-U}, R^{O_r-O_p}, R^{O_r-P}$$

(Eq. 4-2-2)

With

$R^{R_1-U} \subseteq R_1 \times U$	is the set of relations between rules and users
$R^{R_1-T} \subseteq R_1 \times T$	is the set of relations between rules and tech tools
$R^{R_1-O_p} \subseteq R_1 \times O_p$	is the set of relations between rules and operators
$R^{R_1-O_r} \subseteq R_1 \times O_r$	is the set of relations between rules and the organizing
$R^{R_1-P} \subseteq R_1 \times P$	is the set of relations between rules and purpose
$R^{U-T} \subseteq U \times T$	is the set of relations between users and tech tools
$R^{U-O_p} \subseteq U \times O_p$	is the set of relations between users and operators
$R^{U-P} \subseteq U \times P$	is the set of relations between users and the purpose
$R^{O_r-U} \subseteq U \times O_r$	is the set of relations between organizing and users
$R^{O_r-P} \subseteq P \times O_r$	is the relation between organizing and purpose
$R^{O_p-T} \subseteq O_p \times T$	is the set of relations between operators and tech tools
$R^{T-P} \subseteq T \times P$	is the set of relations between tech tools and purpose
$R^{O_r-T} \subseteq O_r \times T$	is the set of relations between the organizing and tech tools
$R^{O_r-O_p} \subseteq O_p \times O_r$	is the set of relations between tech operators and the organizing
$R^{O_p-P} \subseteq O_p \times P$	is the set of relations between tech operators and the purpose

Sometimes tech tools are so intertwined with humans that it is impossible to imagine their behaviour separately. For example, the combination of CPS and a human constitutes the augmented human, and connected humans emerge in the case of equipping humans with at least one cyber element. Moreover, on many occasions, users and operators are the same person or group. Put differently, a social entity can take more than one role in the architecture. These facts prompted us to consider  $U$ ,  $T$ , and  $OP$  as  $C$ .

So, let's consider the following:

$$C = U \cup O_p \cup T \quad (\text{Eq. 4-2-3})$$

Then:

$$\text{GPCM} = \langle R_i, C, O_r, P, R' \rangle \quad (\text{Eq. 4-2-4})$$

With:

$$R' = \{R^{R^i-C}, R^{R^i-O_r}, R^{R^i-P}, R^{C-P}, R^{O_r-C}, R^{O_r-P}, R^C\}$$

$R^{C-P}$  is the set of relations between the components and the purpose

$R^{O_r-C}$  is the set of relations between the organization and the components

$R^{R^i-C}$  is the set of relations between the rules and the components

$R^C$  is a set of interactions between components.

Figure 16 illustrates the GPCM.

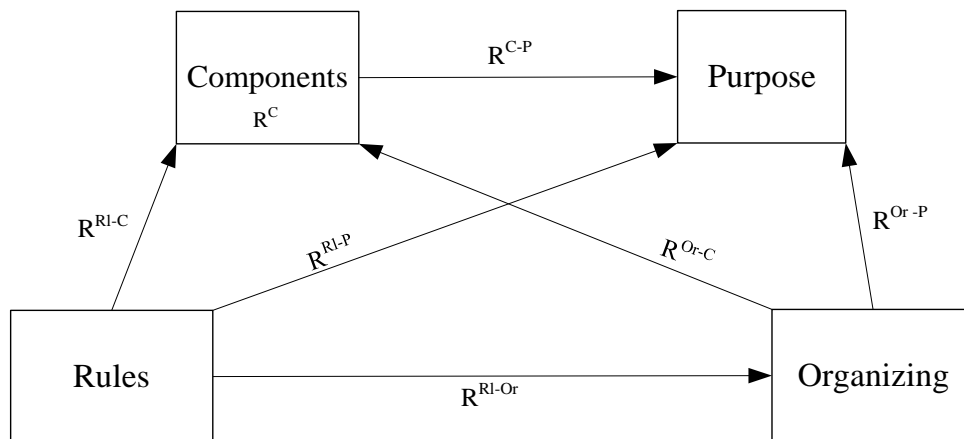


Figure 16 Graphical representation of GPCM

### 3.2.3.2 Hierarchy of CPHS's Activity

Each activity is performed through actions that include one or a set of operations that are executed by CPHS components. Figure 17 shows the hierarchical structure of CPHS activity.

Since the purpose of the CPHS has a high level of abstraction, it is broken down into actions to make it understandable and achievable. An action refers to the mobilization of a set of components to accomplish a goal. In this regard, a set of tech tool(s), user(s) and operator(s) can be employed in a single action, and conversely, each one can contribute to

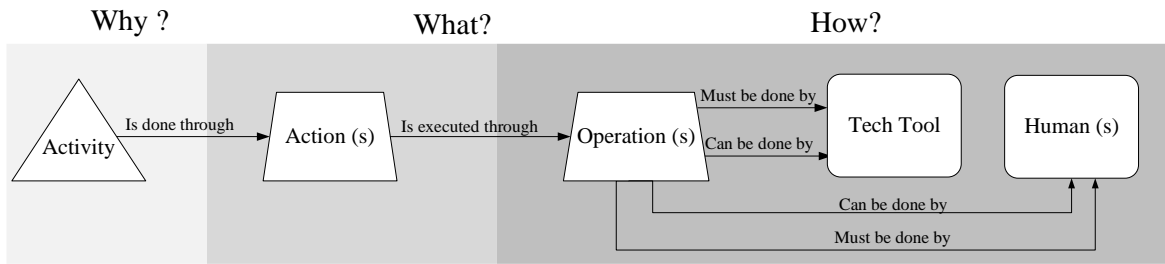


Figure 17 Hierarchical activity structure

one or several actions. Figure 18 depicts the action patterns that can be seen in CPHS activity. Atomic action is the most straightforward pattern that exists in CPHS activity. Collaborative patterns are composed of a set of atomic actions. Due to the technology advancement, multitasking is expanding in intelligent systems. Thus, each CPHS component can be involved in more than one action of the system and shape multi-action patterns. A hybrid pattern is formed when multi-action and collaborative patterns are joined.

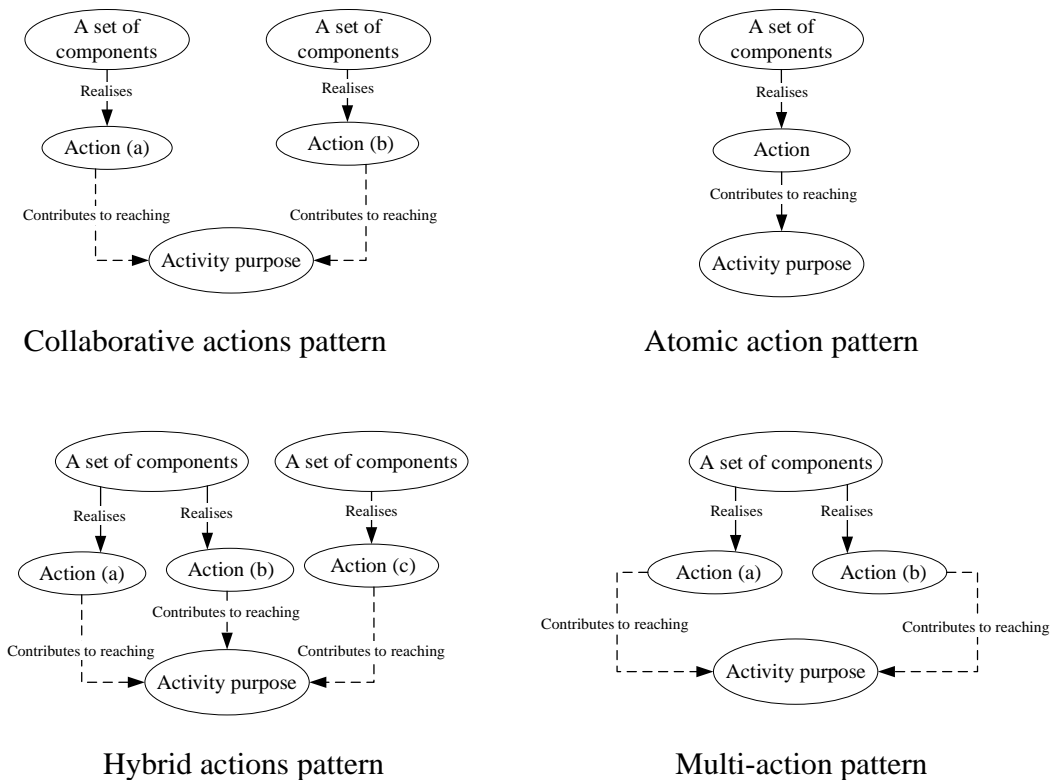


Figure 18 Action patterns in CPHS activity

If we unpack an action, it contains one or several operations that components should perform. An operation in CPHS is defined as the tiniest meaningful unit of work relating to the receiving (energy, matter, people, or information (EMPI)), analysing, decision-making, or executive action (physical or non-physical). We can formulate the actions as follows:

P translates into a set of actions to be performed

$O_r$  is the set of necessary operations to realize the actions.

$R^{Or-P}$  organizes operations into actions.

$R^{Or-C}$  assigns each operation to a component in charge of the execution of that operation.

$$P = \{a_i, i \in A\} \quad (\text{Eq. 4-2-5})$$

A is the set of action names

$$O_r = \{a_{ij}, i \in A, j \in A_i\}$$

With

$$\forall i \in A, A_i \subset \mathbb{N}^*$$

$$R^{Or-C} : O_r \rightarrow C$$

$$R^{Or-P} : O_r \rightarrow P$$

$$R^{Or-C} \cup R^{Or-P} \Leftrightarrow \varphi : O_r \rightarrow C \times P$$

$$R^{C-P} : C \rightarrow P$$

$$(c_k, a_i) \in R^{C-P} \Leftrightarrow \exists x \in O_r \mid (x, a_i) \in R^{Or-P} \text{ and } (x, c_k) \in R^{Or-C}$$

By using Eq. 4-2-4 in Eq. 4-2-3

Then:

$$GPCM = \langle R_i, C, O_r, P, \{\varphi\}, R'' \rangle \quad (\text{Eq. 4-2-6})$$

$$R'' = \{R^{Ri-C}, R^{Ri-Or}, R^{Ri-P}, R^C\}$$

We can translate the relations between rules and other concepts as follow:

$R^{Ri-C}$  associates a specific rule with a particular component.  $R^{Ri-C}$  is generally related to the properties or behaviours of the component.

$R^{Ri-P}$  associates a specific rule with the purpose.

$R^{Ri-Or}$  associates a specific rule with a particular operation or sequence of operations. It is generally related to conditions of operations or sequential flows that have to be met.

$R^C$  are shaped by means of interactions, as shown in Figure 14.

### 3.2.3.3 Instantiation of GPCM

GPCM should be expressed by modelling languages (preferably visual) to be practical for modellers. A set of modelling languages should be deployed for these specifications. Table 11 depicts our proposed collection of modelling languages well-fit for GPCM.

Table 11. Modelling languages for GPCM specifications

Modelling language	Aim	Covered concepts of GPCM
SysML Requirement Diagram	To describe the constraints on the system.	$R_i, R^{RI-P}$
SysML Block Diagram	To identify and describe T, U, and Op as well as their relationships and contents (Properties, operations, constraints).	$C, R^{RI-C}, R^C$
BPMN Diagram	To represent the flow of the operations, operations assignments and manifest the constraints on operations.	$\varphi, P, Or, R^{RI-Or}$

Rules (i.e., technical, social, and ethical) are often viewed in engineering fields as requirements that describe one or more capabilities or conditions in the system (generally expressed abstractly) that always have to be satisfied. The SysML requirement diagram defines a system's functional and non-functional requirements and shows their relationships. Furthermore, it depicts how the requirements can be met.

Each component of the system can be regarded as a block. The block diagram in SysML defines the features of the components and the relationships between them. The anatomy of each block generally includes values, operations, and constraints. Values are structural features of a block. An operation is defined as a behavioural feature showing what the block can perform.

BPMN provides a graphical notation to represent a suitable static view of a system. We use BPMN to show how operations are assigned to components. At this stage, we show the system by a pool depicted as rectangles with a label (See Figure 19).



Figure 19 CPHS pool

To demonstrate that certain components are responsible for performing specific operations, we divide the pool into lanes (rectangles within a pool) such that each lane is associated with a particular component. An operation is a work that is performed and represented by a rectangle inside the lanes. Operations should be defined in the form of receiving (energy, matter, people, or information), analysing, decision-making, or executive action (physical or non-physical). Depending on the conditions expressed, gateways (diamond shapes) may be utilized to

determine diverges and sequence convergence. Sequence flows (arrows with a solid line and filled arrowhead) connect the operations and gateway within the pool.

$R^{RI-Or}$  includes the constraints imposed on the operations. Temporal constraints impose restrictions on temporal operations. For example, if operation “A” takes less than ten minutes, the next operation is “B”; otherwise, operation C will be executed. Conditional constraints can also restrict an operation. It means that an operation cannot be executed if a specific condition is not met. If a specific input (like a message) is not received, an operation may face input constraints preventing execution. Inter-operation constraints refer to the hindrances related to the sequence of operations. For example, operation “A” cannot be executed before operation “B”. We can find many works that tried to show how these constraints can be applied in BPMN (Awad et al., 2009; Cheikhrouhou et al., 2013; Combi et al., 2017; Geiger, 2013; Parody et al., 2012).

### 3.2.4 GPCM: Illustrative case

Let's have a look into robotic surgery as a CPHS (see Figure 20). The user of robotic surgery is a patient (C) who benefits directly from robotic surgery activity to remove a tumour (P). The surgeon is the main operator (C) in the CPHS to provide major services to the patient. Two supervisors and an assistant surgeon are the other system operators (C). Anaesthesia ( $a_1$ ), incision ( $a_2$ ), tumour removal ( $a_3$ ), and closure of the incision ( $a_4$ ) are sequential actions of the surgery, which are supported by two monitoring actions ( $a_5$  and  $a_6$ ).



*Figure 20 Robotic surgery*

The storyline of the activity is as follows. The robotic surgery must be supervised from the beginning to the end (R1). So, a supervisor should initially attach the sensors to the patient ( $a_{15}$ ). By doing so, the vital sign monitor can receive the patient's data ( $a_{25}$ ) and show it on the screen ( $a_{35}$ ). The supervisor watches the vital sign monitor ( $a_{25}$ ). There is a requirement that the vital signs should be displayed ( $a_{25}$ ) every second ( $R^{RI-Or}$ ), and the supervisor should be

able to read the vital sign monitor from a minimum distance of two meters ( $R^{R1-C}$ ).

Before starting surgery, the supervisor should make sure that the vital signs data are available ( $a_{55}$ ), show the green light to the surgeon ( $a_{85}$ ), and then start monitoring the patient's condition ( $a_{75}$ ). If the supervisor detects any abnormal condition during the surgery, he warns the surgeon ( $a_{105}$ ). During the surgery, the supervisor may receive information from the surgeon or the second supervisor to obtain better awareness to analyse the patient's condition. The second supervisor visually monitors the activity ( $a_{16}$ ) and decides ( $a_{26}$ ) whether alert the surgeon about an adverse environmental event ( $a_{36}$ ) or not. When the surgeon is sure of the supervisor's readiness, he ( $a_{11}$ ), he announces the beginning of anaesthesia ( $a_{12}$ ). The surgeon starts the surgery by choosing the speed ( $a_{31}$ ), and a robot (C) initiates its position ( $a_{41}$ ) and performs anaesthesia ( $a_{51}$ ) without the surgeon's involvement. Upon anaesthesia, the surgeon announces the end of anaesthesia ( $a_{61}$ ).

After each stage of the surgery, according to the conditions, the surgeon must decide whether to continue the surgery or not ( $a_{12}$ ,  $a_{13}$ , and  $a_{14}$ ). The incision is fulfilled with the low participation of the surgeon. So that the surgeon gives the robot the necessary information about the incision ( $a_{22}$ ), and then the robot adjusts its position ( $a_{32}$ ) and requests the surgeon to confirm the incision ( $a_{42}$ ). Once the surgeon approves it ( $a_{52}$ ), the robot performs the incision ( $a_{62}$ ). Tumour removal must be done by the surgeon ( $a_{23}$ ), who uses a control unit to move the robotic arms. The surgeon accomplishes the closure ( $a_{34}$ ) by using robotic arms, but if he feels tired ( $a_{24}$ ), he can leave the closure to the assistant ( $a_{44}$ ). Once assistance is informed ( $a_{54}$ ), she performs it ( $a_{64}$ ).

Figure 21 depicts the purpose-centric model of the robotic surgery. SysML Requirement Diagram, BPMN, and SysML Block Diagram are presented to model the specifications of the purpose-centric model of robotic surgery as follows: Figure 22 exhibits the SysML Requirement Diagram for two actions. The BPMN diagram of robotic surgery is given in Figure 23. An example of the SysML Block Diagram is illustrated in Figure 24 for two components of the robotic surgery.

A deeper insight is given into monitoring vital signs. Many sensors collect data regarding the patient's life functions (e.g., pulse rate, and blood pressure). These data are processed and depicted to the supervisor by a vital sign monitor. According to the displayed information, the supervisor should decide whether to warn the surgeon (or his assistant) or not. Some factors may affect his behaviour. For example, if he is distracted, he may not pay enough attention to the signal monitor and expose himself to losing some essential information for decision-making. The supervisor's decision can affect other actions performed and, consequently, the CPHS behaviour. This will be modelled in the second layer of the framework (BCL), where we show how CPHS components behave and how the behaviours are modelled.



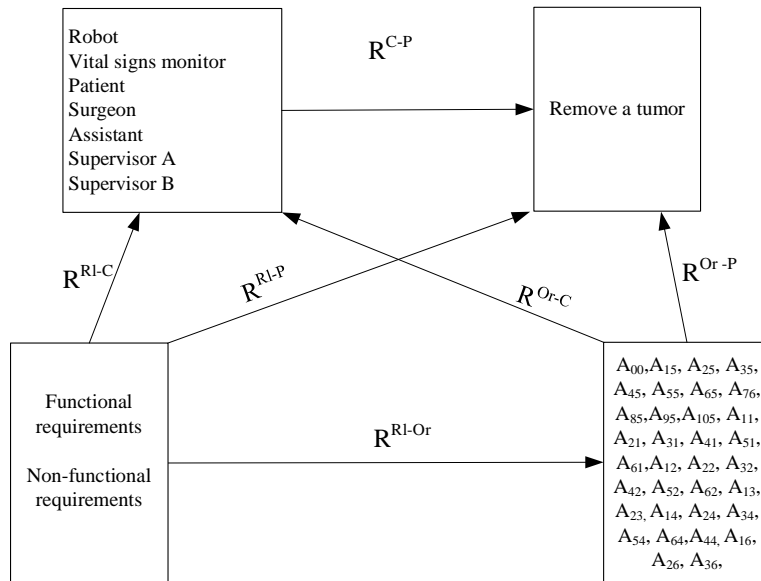


Figure 21 Purpose-centric model of the robotic surgery

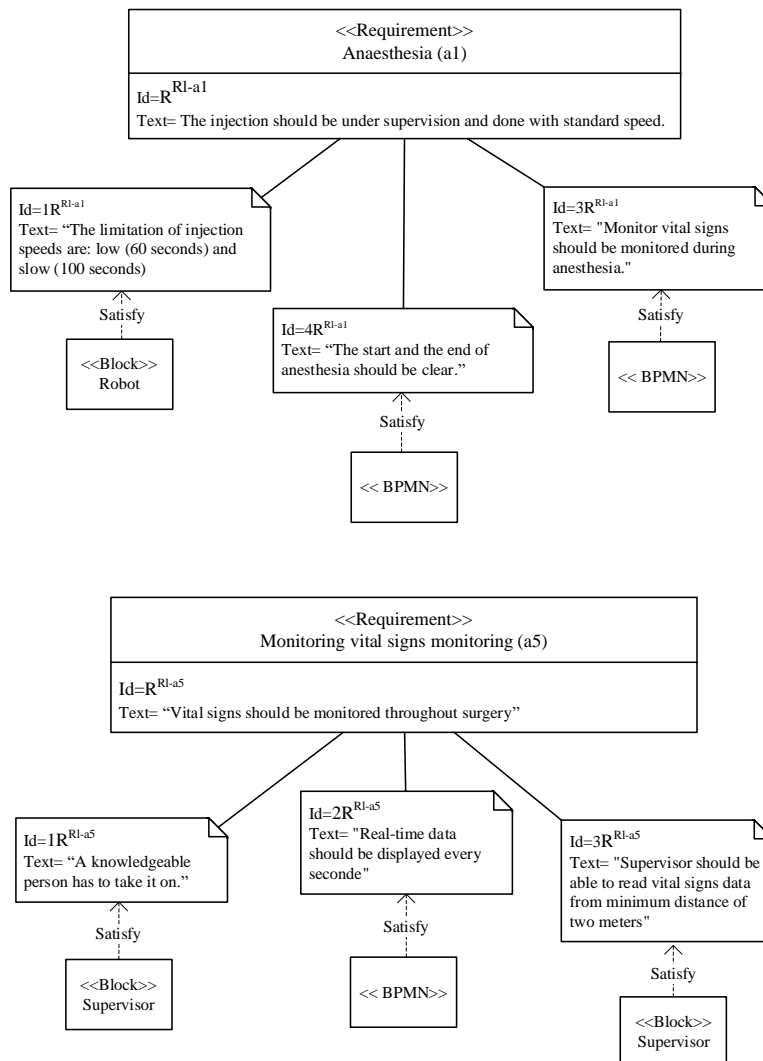


Figure 22 An illustration of  $R_I$  and  $R^{RI-P}$  by SysML requirement diagram for Anaesthesia and vital signs monitoring actions

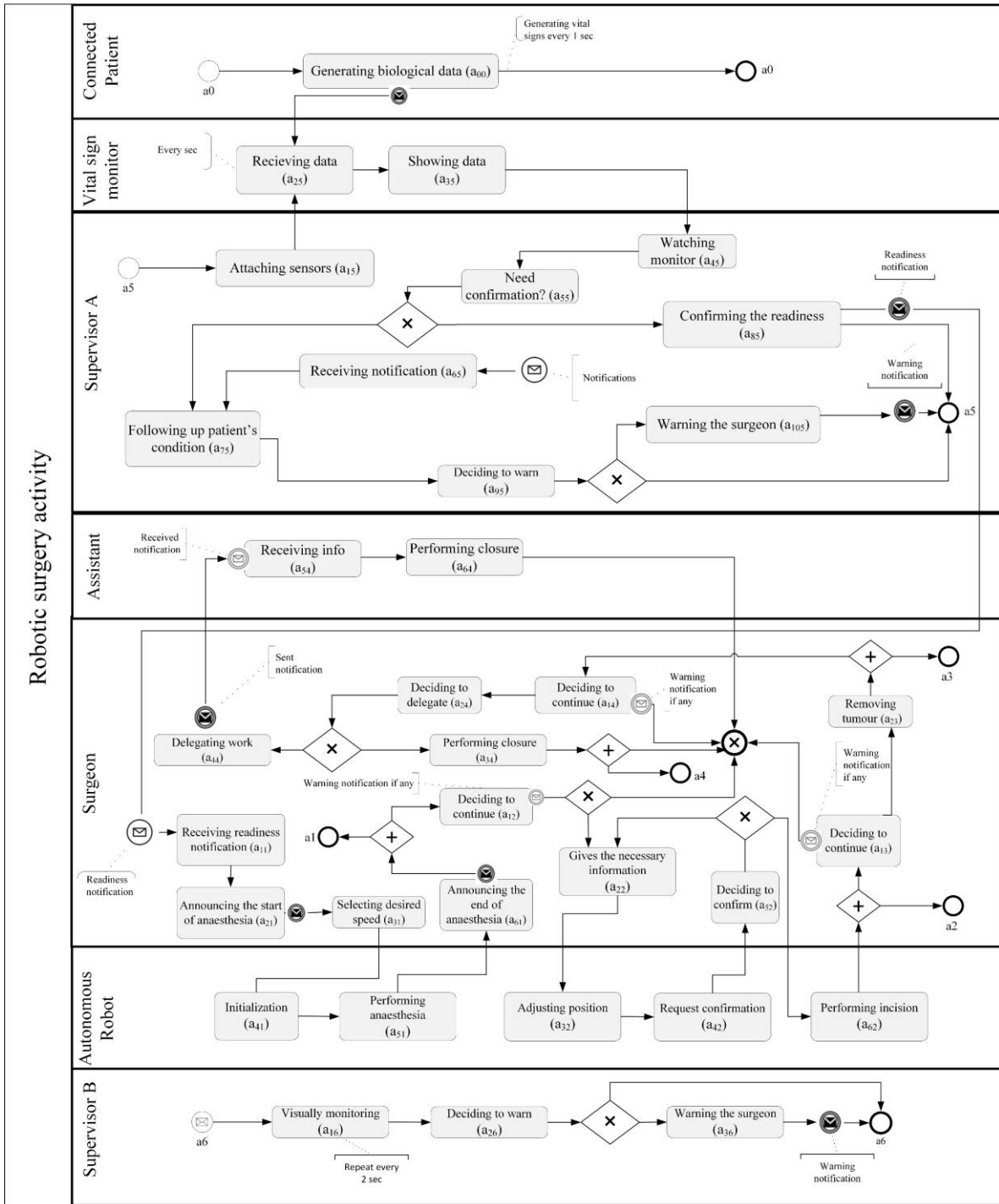


Figure 23 BPMN diagram of robotic surgery

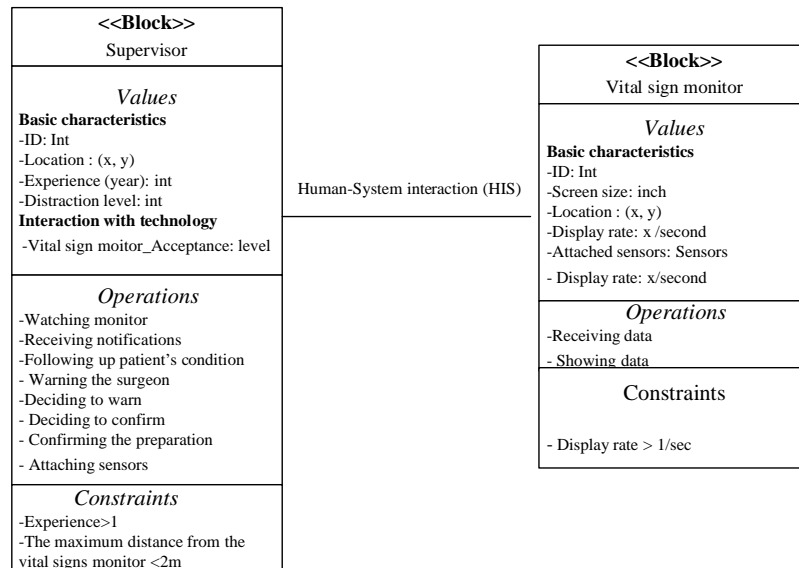


Figure 24 An illustration of  $C$ ,  $R^{Rl-C}$ ,  $R^C$  by Block diagram

### 3.2.5 PCL summary

To answer the first research question, we began with the purposefulness of CPHS and contended that usability is the primary purpose of any CPHS. In this regard, we presented pragmatism, humanism, and instrumentalism as the three main factors of CPHS usability.

System behaviour determines how the system achieves its goals. We studied CPHS behaviour and explored the potential interaction between CPHS components. The intelligence of CPHS refers to the way that the interactions are managed, controlled, and improved within the system. We discussed the CPHS intelligence and argued that the intelligence structure might be distributed (Homogeneous or Heterogeneous) or Centralized (Human-based / AI-based).

We used AT as a proper lens for studying CPHS from a holistic view angle. To the best of our knowledge, it was the first application of a social science theory to describe CPHS. Since classic AT deals with simple artefacts, it was a need to adapt the architecture to the new CPHS ecosystem. To go forward, we proposed a GPCM that can explain human-human and human-tech tool interactions, technology acceptance, HCA, as well as ethics and rules of technology within CPHS through a formal structure. GPCM has been formulated by FOL to provide a logical approach for modellers to understand the system. We showed how GPCM could be modelled through well-known modelling languages (i.e., SysML and BPMN), which are transparent system representations for engineers and modellers. Ultimately, an example of robotic surgery was presented as an illustrative case for GPCM.

## 3.3 Behaviour-Centric Layer (BCL)

BCL deals with the CPHS simulation model and pays particular attention to behaviour modelling, which plays a critical role in constructing the simulation model of a system. In line

with this, first, we exhibit the general view of the CPHS simulation model. Then, we discuss how components can behave within CPHS. This prompted us to propose a new architecture to model the behaviours of CPHS components. Next, we give GBCM based on HiLLS formalism that enables modellers to develop a comprehensive and parameterized simulation model of CPHS, including the behavioural models of its components.

### 3.3.1 CPHS simulation model

System theory differentiates between open, closed, and isolated systems. Open and closed systems require inputs to be dynamic or start their dynamicity. According to a definition provided by (Mele et al., 2010), open systems can exchange energy, matter, people, and information (EMPI) with the environment. There is just an energy exchange in closed systems, while any exchange of elements does not occur in isolated systems. From this point of view, CPHS can be regarded mostly as an open, in some cases, closed, and rarely an isolated system. Accordingly, the CPHS model for simulation may need inputs and outputs as well. Moreover, it requires the models of the system, passive and active components, behavioural constituents, and potential pools. The system model is destined to keep system parameters and establish the relations between active components in such a way that the CPHS achieves its goal. Components are either passive or active constituents in CPHS. A passive component has no behaviour. In other words, they should be used and cannot react to stimuli. In contrast, an active component manifests the behaviour. The lowest level of the CPHS model is associated with the models of behavioural constituents that are developed inside the active component models to contribute to shaping the behaviour of the component they belong to. To better manage a set of active or passive components, pools are designed. Suppose we have a set of passive components that can be seized and released by active components. In this case, the pool model should be developed to facilitate resource management and handle seizing and releasing components. Figure 25 gives a general view of the CPHS model.

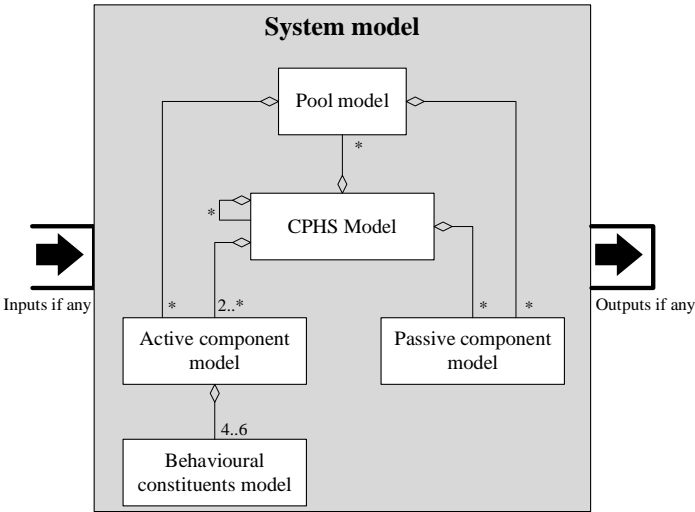


Figure 25 General view of the CPHS simulation model

To understand the mechanisms governing the dynamicity of a complex system, we must be able to model the behaviour of each system's component (Active ones). We describe the behaviour of a component as a change that may be initiated by the internal state or external events and lead to outputs, modification in itself or other system components.

### 3.3.2 Component behaviours

Behavioural models of active components provide a realizable description of how a component performs its operations. As indicated in the GPCM, CPHS's components are users and operators (as social entities) as well as tech tools (as artefacts). Social entities can indeed be manifested as individual humans, groups, and also social organizations. Here, we do not address the behaviours of social organizations and crowded groups for the reason that they need specific behavioural models which lie beyond the scope of our study. We only investigate the behaviour of tech tools and humans who get involved in CPHS individually. Figure 26 exhibits the behaviours of humans and tech tools and how the components contribute to achieving the system's purpose.

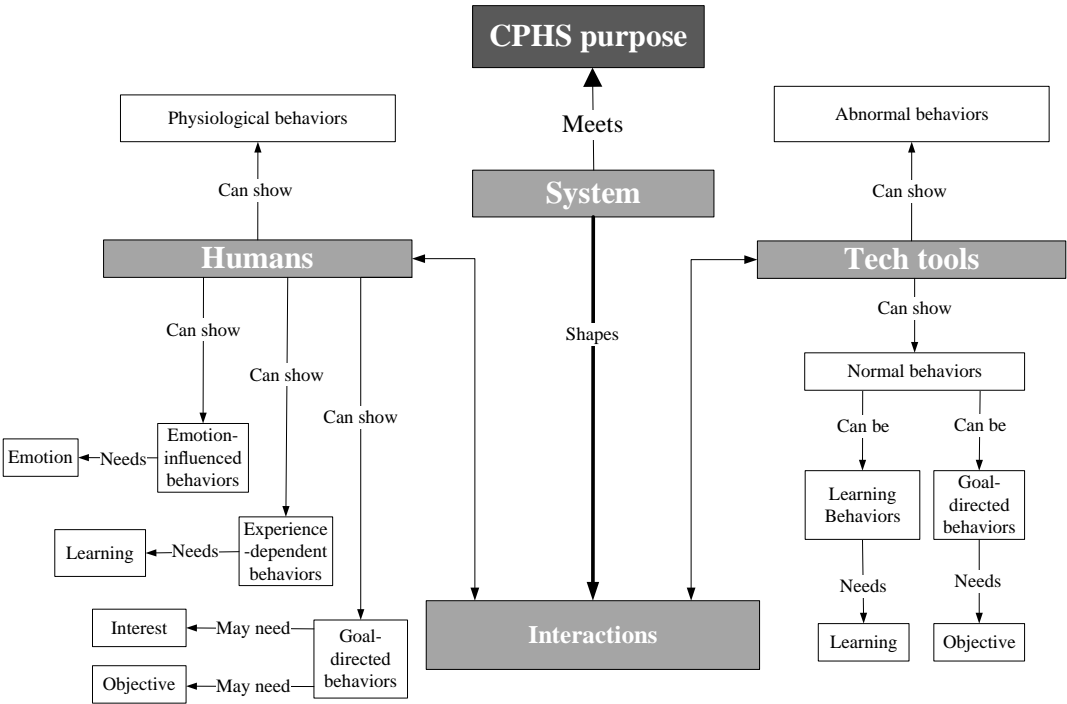


Figure 26 Individual behaviours in CPHS

#### 3.3.2.1 Tech tool behaviours

Tech tools in CPHS can manifest normal and abnormal behaviours. Any behaviour that conforms to norms or pertains to expected typical patterns is considered normal. In contrast, abnormal behaviour can be imagined for tech tools if their normal behaviours are somehow disturbed. Normal behaviour can be divided into goal-directed and learning-based. Goal-

directed behaviours are oriented toward achieving a particular goal by using a simple function or complex algorithms (e.g., an automatic door activates opening and closing functions when it detects a motion). In other words, the goal represents some desired final state of the component (Georgeff et al., 1998). Goal-directed behaviours may lead to self-configuration, which is an ability that allows a tech tool to adjust its behaviour in the face of change by modifying its configuration autonomously. For example, in the event of power fluctuations, the automatic door enters the safe mode, reconfigures itself, and returns to service.

In learning-based behaviours, tech tool uses learning algorithms and cumulative data and information to obtain context and situation awareness or adapts the goal or action plan to novel conditions. In fact, learning abilities allow tech tools to acquire novel behaviour, reinforce it or adapt their behaviours to the environment through learning algorithms. As discussed in chapter 1, tech tools can contribute to sensing, decision making and action. In this regard, the learning process can help a tech tool improve its sensing, decision-making, and acting abilities based on experience.

### *3.3.2.2 Human behaviours*

Human-being in CPHS can be seen as individuals and populations (crowd). This distinction is rooted in the fact that the behaviour and properties of an individual may differ from a group (Goldstone & Gureckis, 2009). The use of crowd behaviour is generally reported in IEMS (Xiong et al. (2013), where the behaviour of evacuees is studied as a whole. According to the literature review, individual human behaviours have received more attention in CPHS. In this regard, our approach for modelling is oriented on individual behaviours.

Humans are in a position to take over various roles in CPHS (Nunes et al., 2018). They generally can react to external stimuli or be self-stimuli to trigger a chain of cyber and physical operations in the system. Although individuals are diverse in personality, bodily characteristics, and abilities, their behaviours can be studied from a general structure. As living beings, humans have biological functions that are largely unconscious and controlled by the autonomic nervous system which may provoke some unconscious behaviours. In order to study human behaviours, our focus is beyond the spectrum of biological functions. We devote ourselves to the way that humans do their operations consciously. These behaviours can be explained as goal-directed, emotion-influenced, and experience-dependent (Luo et al., 2009).

Goal-directed behaviour pertains to a specific operation method to obtain particular outcomes in a given situation (Zwosta et al., 2015). People who show goal-directed behaviour are closer to making rational and optimal choices (Pfister & Böhm, 2008). For example, a driver stops the car when she approaches a stop sign at an intersection. The term emotion-influenced behaviour is used to describe those responses and reactions which appear in the individual because of emotions and feelings. For example, due to stress, an operator decides to call an AGV robot thirty minutes ahead (secondary emotional behaviour), or when we feel threatened by an unexpected event, we stop working (primary emotional behaviour). Jiang and

Vidal (2006) assert that successful modelling of emotional behaviours will enable modellers to come closer to building executable models which approach real human behaviour. Typically, the modification of human behaviours occurs through experience. Humans learn through description, observation, or personal experience. Experience-dependent behaviour refers to the capacity to act upon learning derived from ongoing interactions and engagement with the world.

Human behaviour is complex and multifaceted, such that what kind of behaviour humans show depends to a large extent on the conditions in which they are situated. For example, experienced behaviour is dominant in iterative conditions, whereas goal-oriented and emotional behaviours are more prevalent in dynamic and not experienced conditions. Although the segregation of human behaviours by theoretical constructs brings a good understanding for modellers, it should be kept in mind that it is impracticable to model human behaviours separately. Because human behaviours are intertwined, and a unified structure is in charge of shaping the different behavioural patterns.

### *3.3.2.3 Requirements for modelling human behaviours in CPHS*

For modellers, goal-directed and learning-based behaviours of artefacts are simplified forms of human behaviours. Although the same artefacts have identical or almost similar behaviours, such is not the case valid for individuals. This issue makes modelling human behaviour much more complex than tech tools because one behavioural style cannot be true for all people.

A set of characteristics and abilities somehow make people behave differently in the same situation. Although biological, physical, and cognitive features can influence an individual's behaviours, we focus on cognitive features more emphasized in CPHS.

Human cognitive features can be divided into characteristics and abilities. Human intellectual abilities (e.g., learning) lead to changes in behaviour and are typically modelled through functions, methods, and algorithms. In comparison, human characteristics help us predict and model an individual's behaviour in a particular situation. The variability of characteristics refers to the range of possible values they can take. According to the degree of variability, the characteristics can be represented by variables (dynamic) or parameters (almost constant). Variable characteristics consistently change, and we should always refer to time  $t$  to determine their values, e.g., emotions. In contrast, parameters are static states with relatively stable values. For example, we can define personality traits as parameters that generally do not evolve during the study (Jones et al., 2009).

To model human behaviours in CPHS, we regard characteristics and abilities that:

- Seem to have a significant influence on behaviour.
- Can be generalized to all intended application domains.
- Have been used and reported within the applications of CPHS



- There is good knowledge about their functional mechanisms and effects.
- Are modellable through available modelling technics.

In this respect, we found that the most influential cognitive features on human behaviours are: Personality (Doce et al., 2010; Ghasem-Aghaee & Ören, 2007; Yilma, Naudet, et al., 2021), Interest (Nunes et al., 2018; Paul & Reddy, 2010; Pew & Mavor, 1998), emotion (Aarts & De Ruyter, 2009; Banerjee et al., 2018; Council, 2008; Duque et al., 2013; Friis-Liby, 2020; Kouicem et al., 2020; Mukhopadhyay et al., 2020; Urban & Schmidt, 2001; Villanueva-Valle et al., 2021; Vinciarelli et al., 2015; Yilma, Panetto, et al., 2021), Human learning and habits (Bonabeau, 2002; Groeneveld et al., 2017; Luo et al., 2009; Pew & Mavor, 1998; Wang et al., 2020), and communication (Ahmad et al., 2019; Albaba & Yildiz, 2019; Domova, 2020; Maitlis & Christianson, 2014; Odden & Russ, 2019; Rom & Eyal, 2019; Vinciarelli et al., 2015). Table 12 describes the essential human characteristics affecting human behaviour in CPHS.

Table 12. Significant human features affecting human behaviour in CPHS.

N.	Feature	Description
1	Personality	<i>Traits are fundamental properties of an individual (McRorie et al., 2009) that do not change in the short term and can affect behaviours. The personality study aims to explain how and why people differ (Revelle &amp; Condon, 2015). There is various classification of human personality based on different theoretical foundations. The importance of personality study in CPHS can be regarded from two standpoints. First, it can contribute to improving tech tools' ability to adapt better to various human characters. Second, it allows the study of the impact of different human personality types on overall CPHS performance.</i>
2	Interest	<i>Nunes et al. (2018) underline that interest is a crucial research challenge in CPHS so that humans may not tend to act in a way that benefits the system if he/she is not interested. For example, imagine an intelligent home that aims to manage energy consumption. In this home, the level of light and temperature are regulated automatically. However, the ethic of technology dictates that residents should also be able to adjust them manually. It means that residents may use manual or automatic adjustments depending on their interests. In this regard, the interest of residents impacts energy consumption. There is also evidence that when technology acceptance is not at the appropriate level, humans are not interested enough in using tech tools that may affect the system's performance.</i>



3	Communication	<p><i>Communication can hint at human-human and human-agent mutual connection (Matsumoto et al., 2006). Scientists believe that communication is not only the exchange of simple messages but also includes both information and the mechanism of understanding. So, interpretation is essential for communication and refers to the quick appraisal through which meaning is assigned to the stimulus. Successful communication requires attention, defined as a highly valued but limited cognitive ability that notices fixing one's mind upon certain discrete aspects of the world in a limited span of time. Distractibility is the opposite of attention and prevents effective communication and obtaining necessary information from the environment.</i></p>
4	Learning	<p><i>Learning aims to gain new knowledge through own or others' experiences and, consequently, obtain correct forms of behaviour. If experience comes from the actor's behaviour is named behaviour learning, and it is called social learning if the experience is acquired from the behaviour of others.</i></p>
5	Emotion	<p><i>There is no definitive definition of emotion, such that more than 92 different definitions have been given in the literature (Kleinginna &amp; Kleinginna, 1981). In simple terms, emotions are internal states related to the short duration of the experience (Gu et al., 2019; Jiang &amp; Vidal, 2006). Emotions are prime factors in the operations of all mental processes (Izard, 2009) that can result in complex behaviour (Kennedy, 2012). In a broad sense, emotions can be either primary, which determines instinctual behaviour, or secondary, which influences cognitive processes, e.g., information perception, commitment, and speed of decision-making (Pfister &amp; Böhm, 2008). Emotions can be caused by beliefs or events that happen in the environment. Generally, emotions are expressed by pair, for example, fear/hope, sad/happy, and calm/tense (Jones et al., 2009).</i></p>

We should underline that the mentioned features are not isolated and generally exposed to social and environmental factors. For example, the emotion of stress can appear as a result of making a mistake at work. Furthermore, discussed features are not independent and seem to have some mutual effects. For example, Seel (2011) asserts that individuals with an openness trait personality are typically intellectually curious and have a more robust learning process. Puica and Florea (2013) argue that personality influences how emotions are updated (decay rate and sensibility).

The high adaptation and adaptive behaviour of human beings are significant parts of the resilience of CPHS, which makes it different from CPS. Adaptation refers to adjusting behaviour by responding quickly and appropriately to new stimuli. The adaptability of individuals is dependent on multiple factors, such as personality traits (Bacanli & Sarsikoğlu, 2021) and degree of learning ability (Groeneveld et al., 2017). For example, neurotic

individuals feel more threatened and stressed in novel situations, and this affects their performance (Judge et al., 2008). Hence, modelling the CPHS resilience seems to require knowledge about personality traits and the degree of learning ability of involved people.

### 3.3.3 Proposed Component Behaviour Architecture (CBA) for CPHS

As mentioned in chapter 2, BDI is one of the most popular frames to model goal-directed behaviours for both humans and tech tools (Georgeff et al., 1998; Vitek & Peer, 2020). In addition, the three-step approach of BDI matches very well with the triple process of the CPS (sensing, decision-making, and action). Limited works have tried to bring learning-based and emotional-based mechanisms into the BDI structure. However, to the best of our knowledge, no unified model has incorporated these three kinds of behaviours.

Each component may follow different behaviour based on the situation and also its nature and abilities. Hence, a general behavioural architecture that can generate multiple useful patterns best meets our needs. Figure 27 presents our proposed Component Behaviour Architecture (CBA) based on BDI that consists of six blocks and potential functions to model goal-directed, emotion-influenced, and learning and experience-based behaviours. Each function is developed when needed and can take into account required factors like personality and interest.

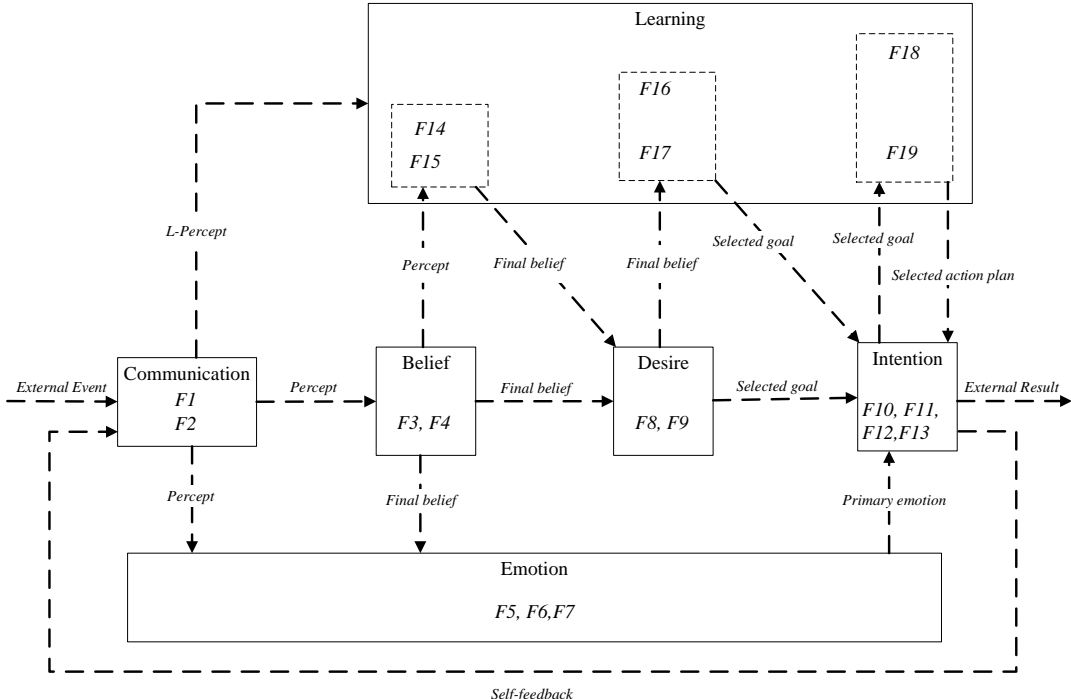


Figure 27 Proposed Component Behaviour Architecture for CPHS based on the BDI model

The functions of the CBA are defined as follows:

- **F1** is a function (may be influenced by emotions and personality in human models) that detects and appraises stimuli. F1 may return a new percept (a meaningful event) or learning

percept (L-percepts). L-percept is a particular form of percept that will be introduced later.

- **F2** is a function (may be influenced by emotions and personality in human models) that receives and interprets environmental stimuli. F2 may return a new percept or learning percept (L-percepts).

- **F3** is a function (may be influenced by emotion, interest, and personality in human models) that receives a percept, revises the beliefs, and returns the final one.

- **F4** is a function that asks the final belief from the learning process.

- **F5** is a function that updates the value of emotion according to the percept and returns primary emotion if present.

- **F6** is a function that updates the secondary emotion according to the final belief.

- **F7** is a function that updates the intensity of emotion according to the elapsed time (the decay of emotion). The decay of emotion leads to a gradual return to the initial state over a period of time (Chowanda et al., 1930).

- **F8** is a function (may be influenced by emotion, interest, and personality in human models) that determines the goal according to the final belief.

- **F9** is a function that sends information (Final belief) to request selected-goal from the learning process.

- **F10** is a function (may be influenced by personality or interest in human models) that determines and executes an action plan according to the selected goal.

- **F11** is a function that sends the information (the selected goal) to request the selected action plan from the learning process.

- **F12** is a function that receives primary emotion and selects an action plan.

- **F13** is a function that executes an action plan derived from the learning process.

- **F14** is a function that receives L-percept in the form of (percept, final belief, label) to update learning values.

- **F15** is a function (may be influenced by personality in human models) that receives the information (percept) and uses a learning algorithm to return the final belief.

- **F16** is a function that receives L-percept in the form of (final belief, selected goal, label) to update learning values.

- **F17** is a function (may be influenced by personality in human models) that receives the information (final belief) and uses a learning algorithm to return a selected goal.

- **F18** is a function that receives L-percept in the form of (selected goal, selected action plan, label) to update learning values.

- **F19** is a function (may be influenced by personality in human models) that receives the information (selected goal) and uses a learning algorithm to return a selected action plan.

### *3.3.3.1 CBA: Behavioural patterns*

The CBA has the capacity to model behaviours in separate and joint forms. This allows modellers to build simple and complex models to represent the behaviours of artefacts and

humans appropriately and with the required levels of complexity. Figure 28 shows the main patterns that can be derived from the architecture.

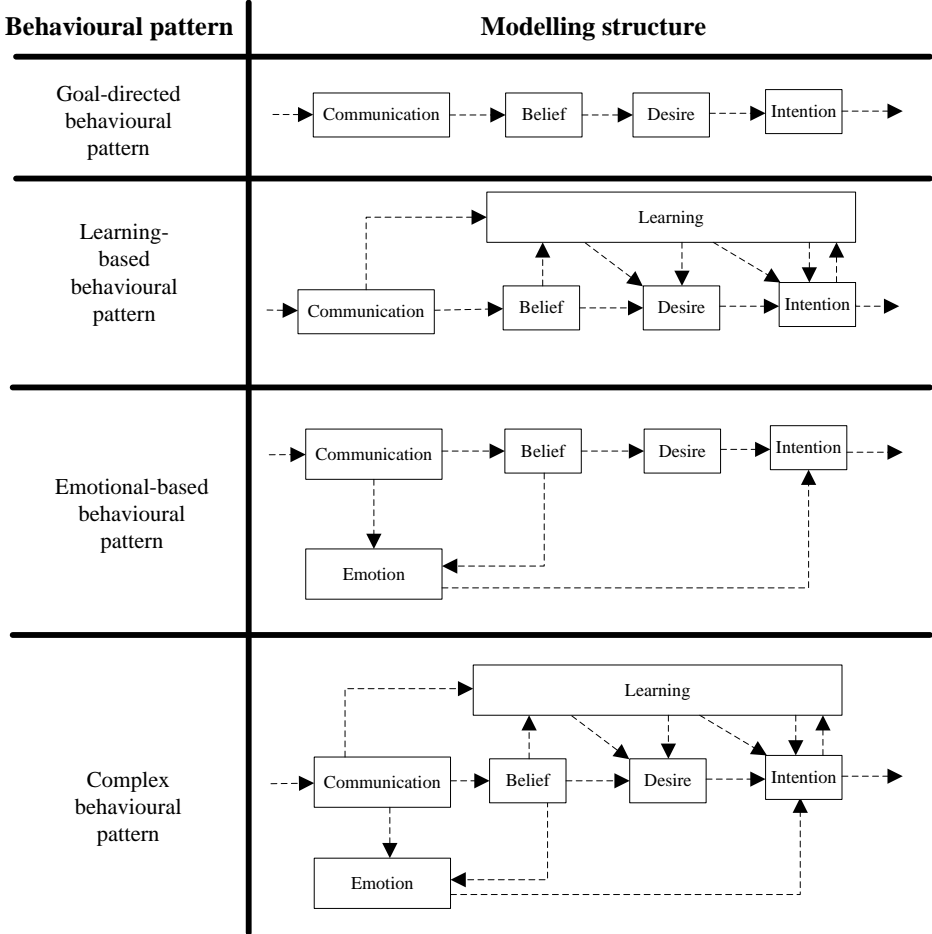


Figure 28 Behavioural patterns derived from the CBA

It should be noted that to model the simple behaviours of tech tools (such as the goal-directed behaviour of an automatic door) that do not have interpretation and decision-making mechanisms, the input and output of the belief and desire blocks are considered the same.

3.3.3.2 CBA: Explanation

In what follows, we explain the proposed architecture in detail. First, the component receives or detects a stimulus resulting from internal or external events. The human communication mechanism is responsible for perceiving, quickly appraising, and developing the meaning of stimuli. By comparison, the communication mechanism of tech tools (e.g., sensors) refers to only perceiving the stimuli without any further interpretation.

If the component is a human, percepts may cause primary emotions (Communication to Emotion path), which cause automatic reactions (Emotion to Intention path). In this regard, primary emotions can directly provoke a predefined action plan. For example, if a machine makes a sudden loud noise, the operator may be afraid and take a few steps back as a quick automatic reaction.

Percepts should be processed to allow the component to gain knowledge of the world and reach a belief (Communication to Belief path). Revising a belief is an interpretation of one or a set of percepts to gain awareness and obtain the final belief. Any new percepts can trigger the revision of beliefs. For example, a person who walks on the street can have two beliefs: safety and danger. He believes in safety by default but interprets percepts (e.g., the street congestion, the time, and the open shops) to revise his belief if needed.

Secondary emotions require second thoughts and are appeared in response to the final belief. Thus, the belief revision can cause secondary emotions (Belief to Emotion path). In the previous example, if the person concludes that he is in danger, the emotion of fear appears. If the intensity of secondary emotions decreases over time, we call it the decay of emotion, which is generally related to personality (Puica & Florea, 2013).

According to the final belief, desire selects a goal that should be fulfilled (Belief to Desire path), e.g., a man who believes he is in a dangerous situation may decide to leave the place. Then, an action plan should be selected to determine how to achieve the selected goal, and finally, the plan is executed (Desire to Intention path), e.g., the person takes a taxi to leave the place.

Learning can impact beliefs, desires, and intentions (Belief-Desire-Intention to Learning path). In other words, a component's perception, decision-making, and executive actions can be influenced by learning mechanisms. The learning process helps the component determine the final belief, goal, and action plan by using experiences. When a component has both goal-based and learning-based behaviours, a Basic Reactive Plan (BRP) should be developed to prioritize the behaviours of the component (Maria & Zitar, 2007). It seems that supervised learning and reinforcement learning are most commonly used to model the learning of artificial and human agents, respectively. Both learning approaches use labelled datasets. Accordingly, we take advantage of L-percepts as labelled data related to experiences to train algorithms. L-percepts can be the result of internal events (Self-feedback) or external ones. Let us take a simple example to clear the L-percept context. An operator checks the quality of products. If he detects large paint stains, he recognizes the product as non-conform (Belief), decides to segregate it (Desire), then marks it with a red tag and puts it in a red box (Intention). But the operator ignores medium and small paint stains and sends the products to customers. He continues the same procedure if he does not get feedback on his work. However, if customers return products with medium paint stains (receiving L-percepts), the operator will learn to consider them non-conform. Now consider that the operator has learned very well. However, he will be replaced by a social robot. This robot learns the operator's behaviour through observation and imitates the same behaviour. Put differently, the operator employed BDI to do his jobs and then benefited from L-percepts for learning purposes and to improve his performance. In contrast, the social robot first used the L-percepts for learning and then executed tasks. The learning mechanism resided in the modelling architecture allows modellers to develop both classic and social learning behaviours of components (See 2.3.1.1).

As was the case in the definitions of CBA functions, the functions for human modelling can be influenced by interest, personality and emotions.

It is well agreed that emotions influence the perception, decision-making, and physical actions of human beings. Since there is no consensus on emotion types (Gu et al., 2019), modellers may use various theories and assumptions. As discussed in 2.3.1.3, to model the emotions, a model maker can use semi-formal taxonomies such as OCC, Russell's circumplex model of affects (Puica & Florea, 2013), and four basic emotions (Jack et al., 2014).

Significant evidence suggests that individual differences (personality) have effects on emotions, goal and action selection (Jones et al., 2009), as well as the learning process (Seel, 2011). In this regard, some functions may be influenced by personality. Various personality classifications can be found in the literature, like the big five personalities (Ghasem-Aghaee & Ören, 2007) or the theory of Millon (Canuto et al., 2006). In cases when emotions or personality types under study are limited, modellers may prefer to use their own emotions and personality classes to meet their M&S needs better, like what Puica and Florea (2013) did for their study.

### 3.3.4 Proposed Generic Behaviour-Centric Model (GBCM)

The fundamental premise that system behaviour can be deemed as a discrete-event system is largely accepted in scientific communities. State-transition modelling (STM) is an intuitive technic to model discrete-event systems, especially in the DEVS formalism. GBCM regards CPHSs as a discrete-event system and provides a comprehensive simulation model according to HiLLS, a high-level graphical modelling language based on DEVS. Before we delve into the GBCM, we should spell out the used HiLLS conventions and mechanisms.

#### 3.3.4.1 *Modelling mechanisms within HiLLS formalism*

As explained in 2.3.2, a HiLLS model can consist of H-System and H-class entities. We classify all variables used in H-Systems into parameters and state variables. State variables of an H-System are variables whose values are only changeable by the operations residing in the PTD of the H-System to which they belong. Whereas the parameters define a set of conditions under which the intended H-System operates. Parameter values are usually fixed; however, they can be changed through methods, operations, or messages. Similarly, an H-Classe can possess variables and parameters. Unlike H-Systems, the values of H-Class variables are changeable by calling the corresponding methods.

In some cases, the modelling may require making variables' values visible to other H-Systems or H-Classes. We take it as a convention that the reading of parameter values is always permitted without limitation, but the values of variables are only readable by calling the corresponding operations of H-Systems or the methods of H-Classes. To make it clear, let us have an example. Suppose a machine is responsible for separating the red boxes put them in

the separation zone. The box is considered an H-Class, its colour is a parameter, and X and Y position of the box are variables. Thus, the machine can read the box colour. However, the X and Y position of the box are accessible merely through the methods (Get methods). In this case, the machine needs to use "box.color " to read the colour and call Box.Get.Position.X() and Box.Get.Position.Y() methods to read the position of the box. If the colour is red, the machine can call the Set\_position methods of the H-Class to reposition the box coordinates. Figure 29 shows the machine H-System and Box H-Class in detail.

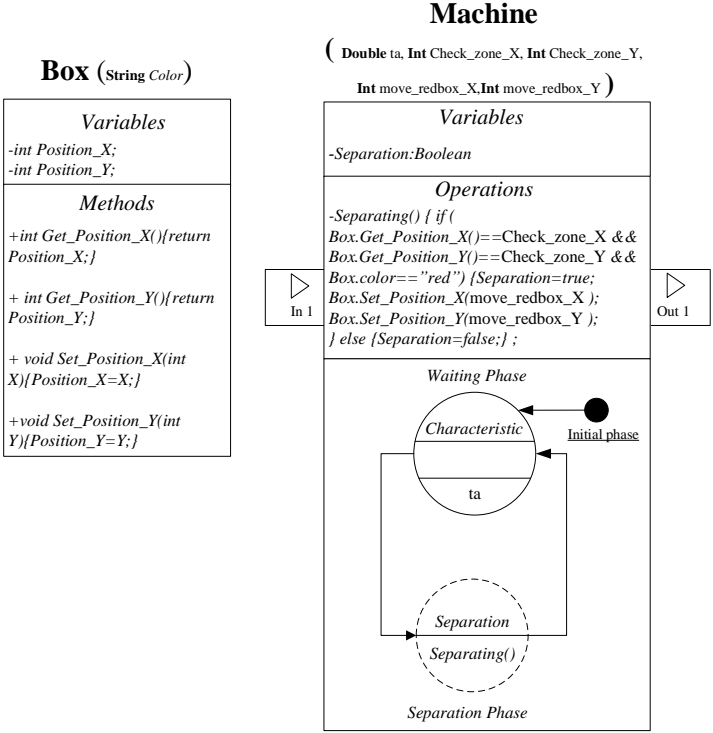


Figure 29 A closer look at the box H-Class and Machine H-Systems

3.3.4.2 GBCM based on HiLLS

As discussed earlier, the general CPHS simulation model contains the system, active components, and their behavioural constituents, as well as potential pools and passive components. All elements of the CPHS simulation model can be considered atomic discrete event systems and drawn through HiLLS formalism. In line with this, first, we develop the HiLLS model of active components based on CBA. Next, the system, pool, and passive components will be modelled in this way. Finally, we introduce GBCM as a guideline for modellers to be able to build a comprehensive CPHS simulation model.

**HiLLS model of active components** is developed based on CBA such that a central H-System so-called active component keeps the component parameters and determines how the behavioural constituents (CBA blocks) are connected together. In simple terms, by defining connections between behavioural constituents, the central H-System can set the component's behavioural pattern. Each behavioural constituent is figured as an autonomous H-System that can interact with each other to perform specific operations. Figure 30 exhibits the active



component and its behavioural constituents via the HiLLS formalism. H-System models depicted in Figure 30 are available with high resolution in Appendix A.

In the following, we explore each of the H-Systems of the HiLLS model of CBA in depth.

*Active component H-System:* By default, the PTD of the active component H-System is in the starting phase. As soon as the initialization message is received, the PTD is transferred to the acting phase that executes the set-up function. This function assigns initial values to the parameters and establishes the links between H-Systems' input and output ports to define the intended behavioural pattern. The number of input and output ports of the H-System models can be variable. In GBCM, the number of ports has been chosen so that the generic model is expressive. For example, the connections of ports to build the complex behavioural pattern (see Figure 28) can be described as follows.

```
{ Belief.In1 = Communication.Out1;
Desire.In1 = Learning.Out1;
Desire.In1 = Belief.Out1;
Emotion.In1 = Communication.Out3;
Emotion.In2 = Belief.Out2;
Intention.In1 = Emotion.Out1;
Intention.In2 = Learning.Out2;
Intention.In2 = Desire.Out1;
Intention.In3 = Learning.Out3;
Learning.In1= Communication.Out2;
Learning.In2= Belief.Out3;
Learning.In3= Desire.Out2;
Learning.In4= Desire.Out2; }
```

**HiLLS model of behavioural constituents** comprises communication, belief, desire, emotion, learning and intention H-Systems.

*Communication H-System:* This behavioural constituent is to receive events (whether internal or external) or detect them by monitoring the changes. Accordingly, the communication H-System has mechanisms to deploy a monitoring approach to event detection and a reactive approach to analyse incoming events. Event detection should be done recurringly at time intervals. Thus, the communication H-System has an active waiting phase to be able to monitor the environment frequently (F1) and also capture incoming events (F2). Using continual and reactive mechanisms, the communication H-System can model constant (Continuous transmission), interval (Periodic transmission), and instant (Event-driven) sensors and also the function of human attention and communication ability. When the component is a human, a quick appraisal is made on received or identified events through which meaning is assigned to the events. In this way, it is possible to model the situations in which different people interpret the same event differently.



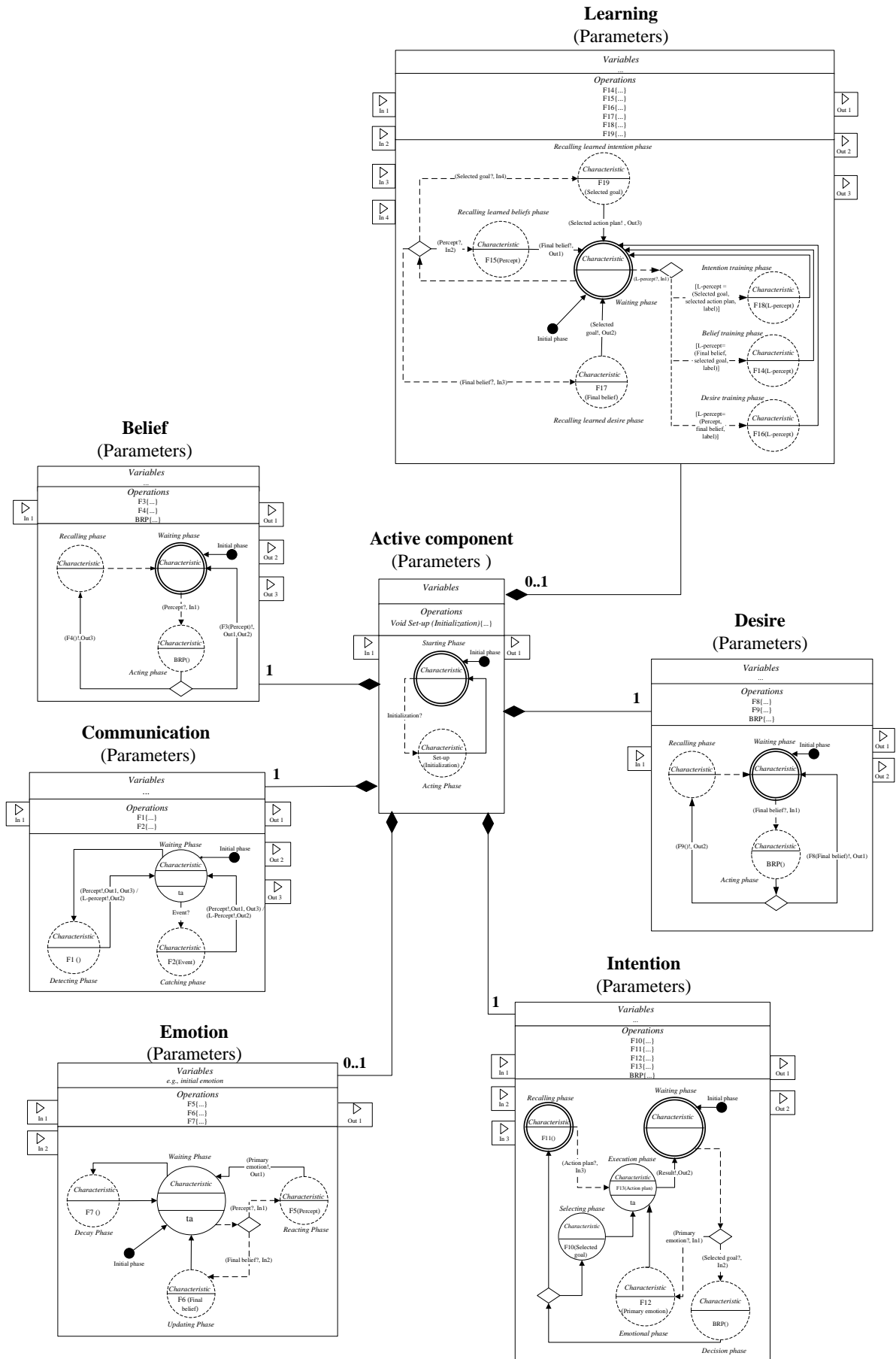


Figure 30 The HiLLS model of CBA

The output of the communication H-System can be a percept or L-percept.

*Belief H-System:* Percepts are received by the belief H-System to be processed and provide a final belief about what is going on. Due to the dynamicity of the world, belief revision may need to use past percepts. In this regard, the variables of the belief H-System can retain past percepts to be used when needed. After belief revision, the final belief is sent to the intended H-Systems through ports. The result of belief revision (final belief) is not necessarily true, specifically when we deal with the belief revision of humans. H-System may need to draw on past experiences as well. In this case, it should decide under what conditions to use past experiences (BRP). If it decides to use past experiences, the belief H-System sends percepts to the learning H-System (F4) and moves to the recalling transit phase.

*Desire H-System:* This behavioural constituent is the heart of the decision-making process and selecting a goal. Its PTD is structured like the belief H-System except that it receives the final belief as input and sends the selected goal as output to the linked H-Systems.

*Emotion H-System:* This H-System is to model the main functions of emotions, i.e., to identify the primary emotions by analysing the percepts, to determine secondary emotions with respect to the final beliefs, and to decay the secondary emotions over time. By receiving any percept, the waiting phase is moved to the reacting phase, which executes F5, sends primary emotion to the associated H-System, and returns to the waiting phase. If a final belief is received, the waiting phase comes to the updating phase in order to determine secondary emotion according to the final belief. The waiting phase of the emotion H-System is active such that "ta" dictates the time interval of decays. Therefore, the decay of emotions occurs at interval (ta) by shifting from the active waiting phase to the transit decay phase.

*Learning H-System:* Learning H-System is able to receive L-percepts as training data to feed databases. Besides, it can use learning algorithms to return the final belief, selected goal, or selected action plan. This H-System consists of three types of learning, each of which includes training and calling. Thus, the designed PTD has six transit phases (i.e., training and recalling phases) and one passive waiting phase. Training phases are triggered by receiving L-percepts. Learning H-System can process three forms of L-percepts (Percept, final belief, label), (Final belief, selected goal, label), and (Selected goal, selected action plan, label). These percepts are used to train belief (F14), desire (F16), and intention (F18) datasets, respectively. Labels in L-percepts indicate the level of success or failure of experiences. Recalling phases are activated when the learning H-System receives a percept, final belief, or selected goal as input in order to return the final belief (F15), selected goal (F17), or selected action (F19) by using learning algorithms.

*Intention H-System:* We develop Intention H-System to determine and execute the selected action plan, react to the primary emotions, and send the action result to the environment or destined H-Systems. The system's state is moved to the emotional transit phase by receiving a primary emotion. This phase has a function (F12) to determine an action plan according to the primary emotion. If H-System receives the selected goal, the H-System goes to the decision

phase, where a BRP function should determine whether the H-System needs to use learned data or not. If the H-System can determine the action plan according to the selected goal, the system's phase goes to the selecting phase and executes a function (F10). Otherwise, it moves to the recalling phase to request the selected action plan from the learning process (F11). Finally, the system turns to the execution active phase to fire function F13 and executes the selected action plan and generates results, if any.

**HiLLS model of the passive component** is designed as H-Classes (See Figure 31.a ) used by active components. To put it differently, passive components need active components to be usable. The parameters, variables, and methods of a passive component depend on the component's expected roles in the system.

**HiLLS model of the system** should be developed as an H-System embracing the general CPHS parameters and possessing a PTD to connect components and initialize their desired parameters (See Figure 31.b ). Based thereon, two phases are embedded in the system's PDT. The PDT is in starting phase and moves to the active phase to execute connecting and initializing operations. Connecting operations should link the input port of communication H-System of desired active components or system model to the output port of intention H-System of destined active components or system model. Then the PDT is moved to the acting phase.

**HiLLS model of the pool** is built by means of H-Classe, which puts into use practical methods (e.g., prioritizing, seizing, and releasing) to manage a set of either active or passive components (See Figure 31.c ).

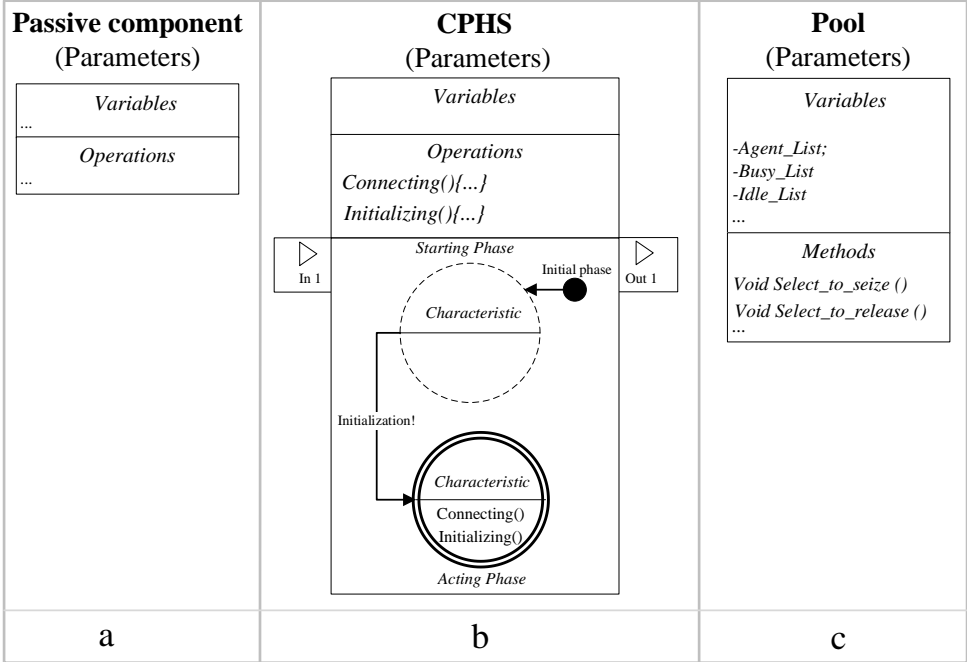


Figure 31 The HiLLS model of the system, pool, and passive component

By replacing the presented HiLLS models in the general view of the CPHS simulation model (see Figure 25), we reach the GBCM, as shown in Figure 32. We should notice that the parameters, inputs, and outputs of the GBCM depend on the context of M&S.

## Generic CPHS model for simulation

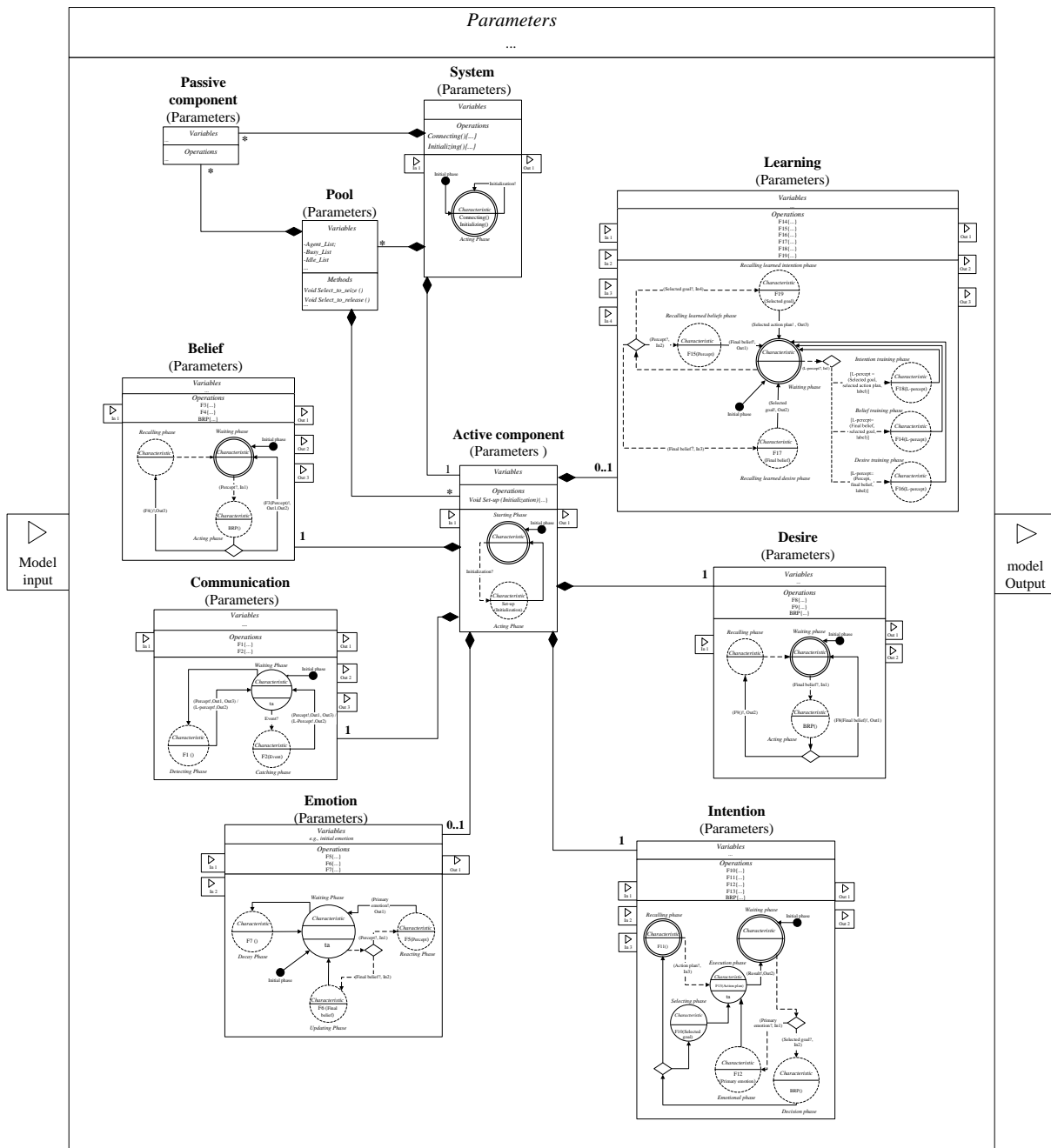


Figure 32 GBCM

### 3.3.5 From GPCM to GBCM: Illustrative case

Here, we aim to put forward an illustrative case to demonstrate how GBCM can be developed in accordance with GPCM. The first step to developing the simulation model is to know the components of the system and the operations they perform. GPCM can identify the components and their attributes through its SysML Block Diagram and depict the operation flow of active components by BPMN Diagram. Although the constraints associated with operations (shown in BPMN) and components (defined in SysML blocks) can be applied through the methods and functions resided in HiLLS, to date, no specific mechanism exists to

verify and validate the constraints systematically.

Consider once again the example of robotic surgery that we had in PCL. Suppose we want to model the behaviour of supervisor A as an active component of the robotic surgery system. To model the supervisor's behaviour, the first stage is to select the appropriate behavioural pattern according to the CBA (See Figure 28). Since we did not take into account emotional factors and learning ability, it seems that goal-directed behaviour is a well-suited behavioural pattern. In the next stage, the supervisor H-System (central H-System) is developed to establish the connections between input and output ports in such a way that the goal-directed behavioural pattern is formed. Certain constraints determined in the supervisor SysML block can be applied in this H-System, e.g., experience level. If this requirement is not satisfied, the supervisor H-System is not able to perform its operations. Figure 33 exhibits the supervisor H-System.

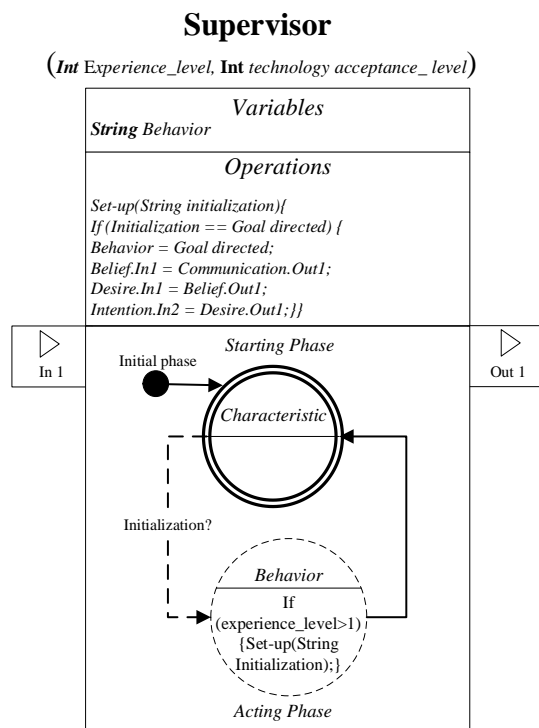


Figure 33 Supervisor's H-System

Now it is time to model behavioural constituents the supervisor. Operations depicted in BPMN should come into effect within communication, belief, desire, and intention H-Systems. Figure 34 guides modellers in determining the H-Systems in which each operation should be implemented.

As shown in Figure 23, the supervisor has eight operations. With respect to the provided guide in Figure 34, a45 and a65 should be developed in communication, a75 in belief, a55 and a95 in desire, and a15, a85 and a105 in intention H-Systems. The modelling of behavioural

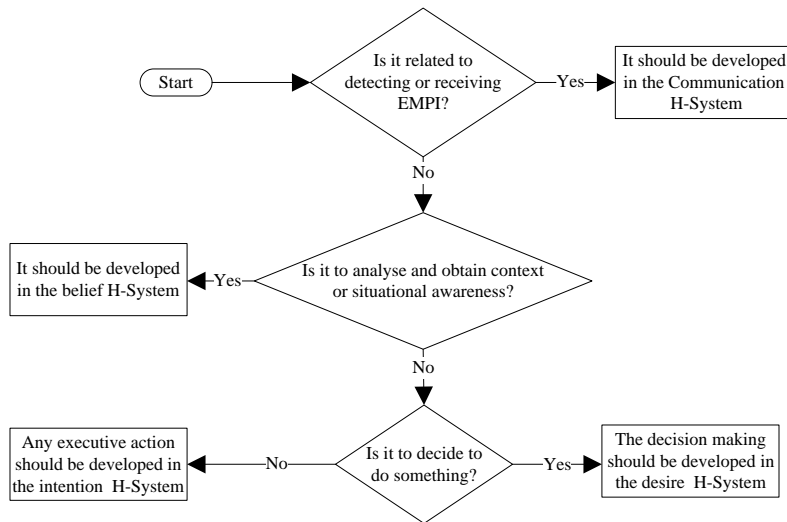


Figure 34 Operations of the BPMN within BDI entities.

constituents begins with building the communication H-System that specifies the data and information the supervisor needs to perform his operations and how to acquire them. As understood, the supervisor's communication H-System uses continual and reactive mechanisms because he observes the data shown by the monitor (a<sub>45</sub>) at regular intervals (attention time interval) and may receive surgery events without a defined time frame (a<sub>65</sub>). The attention time interval depends on the distraction level such that the more distracted the supervisor is, the lower the attention and, thus *ta* goes up. Meanwhile, he is only able to read the monitor data from a distance of two meters (Supervisor constraint depicted in the related block diagram). This constraint is checked in the detecting phase. Figure 35 depicts the communication H-System.

After the communication H-System, we build the belief H-System. The supervisor must

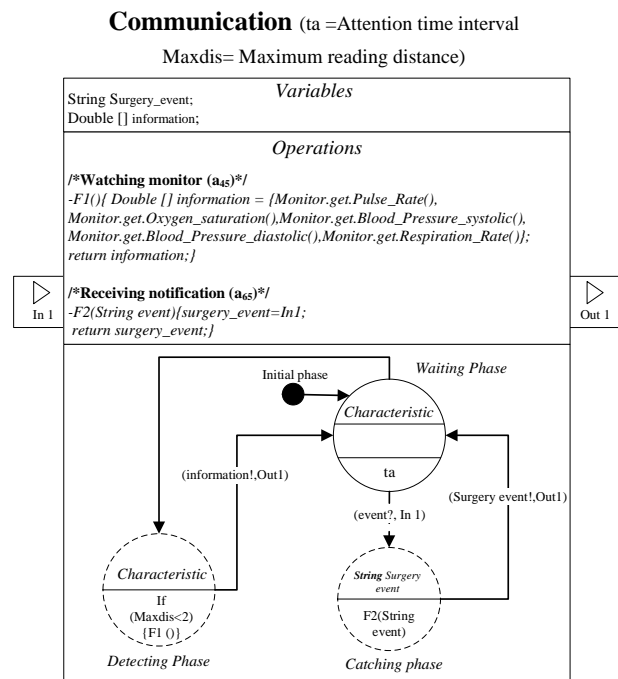


Figure 35 Communication H-System for supervisor behaviour modelling

know the sensor attachment status as well as the patient's condition to choose the appropriate actions. During the surgery, the supervisor analyzes many factors, like body temperature, pulse rate, respiration rate, and blood pressure to determine the patient's condition. To avoid medical complexities, let us consider just blood pressure. If blood pressure drops during the closure of the incision, it may indicate profuse internal bleeding (final belief).

Desire H-System selects a decision (Alerting, connecting, or announcing) based on the final beliefs. The operations of attaching the sensors to the patient, confirming the readiness, and warning the surgeon are formulated in the intention H-System as shown in Figure 36.

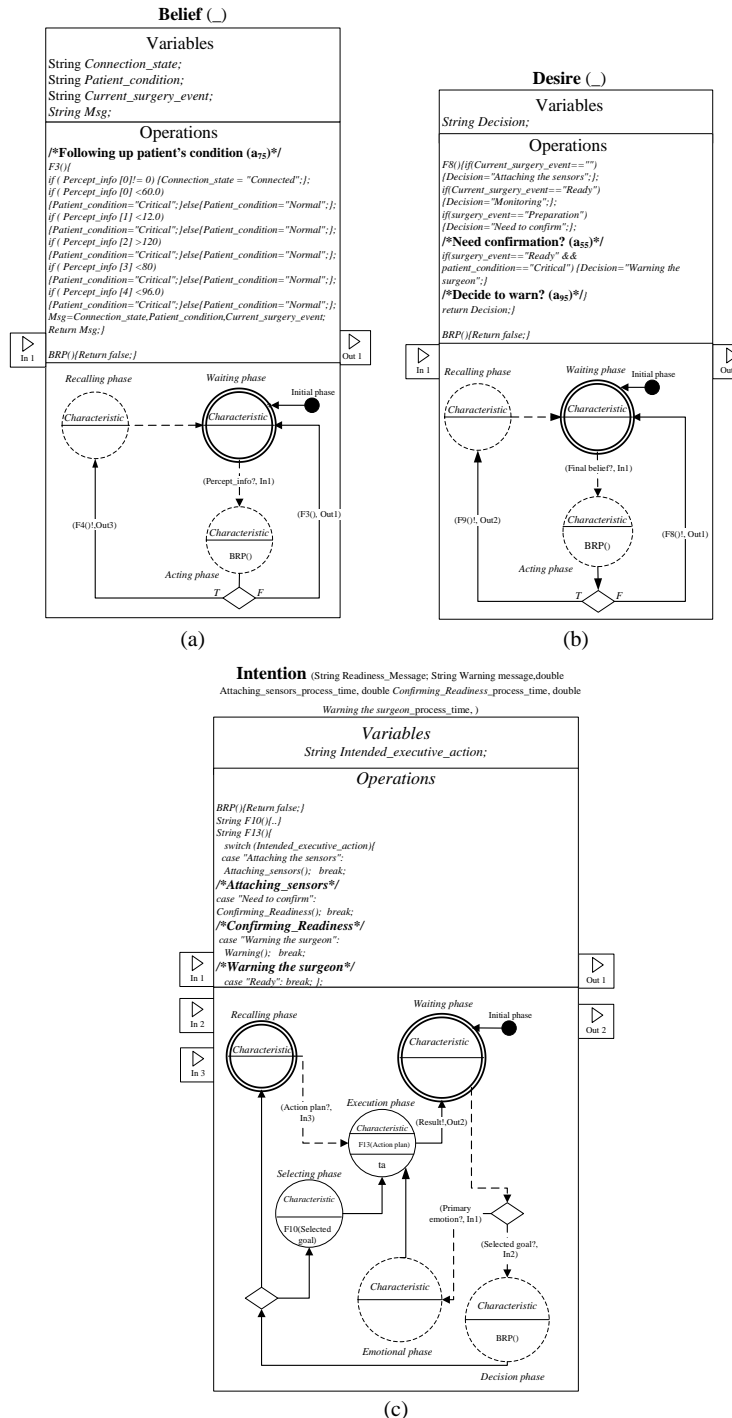
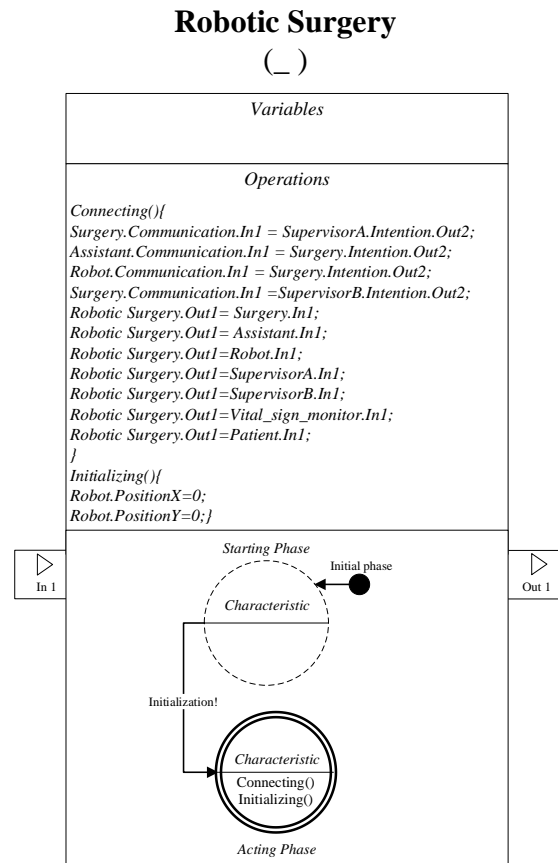


Figure 36 Belief, Desire, and Intention entities for modelling supervisor behaviour

Once behavioural models of all active components are developed, it is time to build the robotic surgery H-System in order to connect the models of components and initialize intended parameters. Figure 37 signifies how the robotic surgery H-System links the input and output ports of models and how the intended parameters are initialized.



### 3.3.6 BCL Summary

The second research question asked how modellers can make a simulation model of CPHS. To answer this question, first, we presented a general view of the CPHS simulation model. As can be understood, the behaviour of CPHS is highly dependent on the behaviour of its components. In this regard, we surveyed and classified individual behaviours of tech tools and humans. Compared to the behaviour of artefacts, human behaviour is much more complex; for this reason, we investigated human behaviour in much more detail and determined the most critical cognitive factors (i.e., personality, interest, communication, learning, and emotion.) that can affect human behaviour in CPHS.

Although the modelling of behaviours has been extensively studied in the literature, no unified structure was found to support all behavioural patterns (i.e., emotion-influenced, learning-based, and goal-directed). Thus, we have proposed CBA based on the BDI that can conceptualize not only artefacts' behaviours but also human behaviours with considering the most critical potential influencing factors in CPHS.



To develop a full discrete-event simulation model of CPHS, GBCM was introduced based on HiLLS formalism that clears the way to make a digital simulation model. Finally, an illustrative case revealed how a CPHS simulation model based on GBCM could be derived from GPCM.

### 3.4 Execution-Centric Layer (ECL)

As the third layer, the ECL is devoted to providing a guide for modellers to execute the CPHS simulation model in order to reach M&S objectives. The GECM shapes the core part of ECL that puts forward the general M&S framework of CPHS based on the System-Model-Simulator (SMS) approach. In this layer, we will define the patterns for the experimental frame (EF) through HiLLS formalism and establish the required connection between EF(s) and CPHS simulation model. Finally, we will display how AnyLogic software can be used as a simulator to digitalize and run the HiLLS models (i.e., EFs and CPHS simulation models).

#### 3.4.1 Generic Execution Centric Model (GECM)

The ECL is based on the System-Model-Simulator (SMS), a well-accepted M&S framework that is an extended form of Zeigler’s Model-Simulator-Experimental Frame (Zeigler et al., 2000). Traoré and Muzy (2006) shared the idea that the model and context as well as the model and frame, should be seen as two pairs that interact with each other through modelling relations. Their idea resulted in a new framework shown in Figure 38.

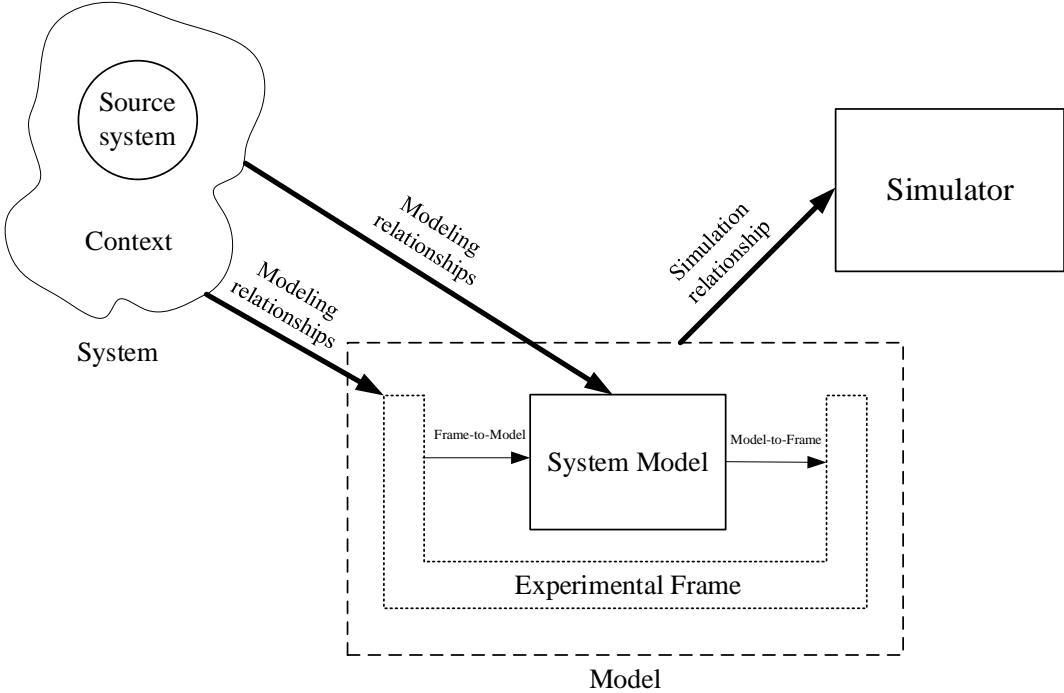


Figure 38 M&S Framework derived proposed by Traoré and Muzy (2006)

In the M&S framework, the intended real or virtual system under study for modelling is

termed the source system (Zeigler et al., 2000). The context refers to the influences (e.g., M&S objectives, assumptions, and KPI measurements) arising from the system environment, which is conceptually not a part of the source system (Traoré & Muzy, 2006). In its most general form, the system model is the system specification for generating behaviour. The Experimental Frame (EF) embraces the system model, which specifies the context. The simulator is the third part of SMS. In a broad sense, the simulator is described as a computation means to run the system model under conditions dictated by EF.

According to Traoré and Muzy (2006), in an effort to properly and successfully develop M&S based on the SMS framework, it is crucial to relate the system to the model and the model to the simulator. Moreover, two internal connections are needed to establish the connections between the system model and EF.

#### *3.4.1.1 Modelling relationships*

First, we discuss the Context-EF relation. EF is to understand the context of the simulation study (Yilmaz & Oren, 2004) and determine the assumptions and potentially a family of experimentations that should be performed within the simulation to obtain analysable results (Traoré & Muzy, 2006). Put differently, EF associates with the context to specify formally the conditions under which the system is modelled. To this end, EF should be designed to manage the modifications that differ from one simulation run to another, if any (Daum & Sargent, 2001). We can assert that the EF is the heart of improvement through testing and analysing simulation results. Once the M&S objectives are defined, EF should be designed to set required indicators and translate desired controls and assumptions into explicit data and parameters regarding the system model. The second relation engages the source system with the system model. GPCM and GBCM are the foundations for understanding the source system and developing the system model.

As discussed in 3.3.1, the CPHS simulation model may need to receive input, send output, or set parameter values. Therefore, the system model may require a particular relation with EF (Frame to model and Model to Frame) to be operable. M&S objective and the type of system model (open or close) determine the appropriate relationship that should be established between EF and CPHS simulation model. Figure 39 depicts potential relationships that may be shaped between EF and the system model, including integrated, coupled, and integrated coupled relationships. The coupled relationship is intended to establish the relationship between EF and the system model only through direct links between their inputs and outputs. In comparison, the integrated relationship refers to the connection of EF and the system model via data to initialise the model. A full connection between EF and the system model is merely attainable via an integrated coupled relationship.

EF can be modelled through HiLLS. To do so, one or a set of EF H-Systems can be developed to reflect context. The PTD of each EF H-System can include phases as follows:

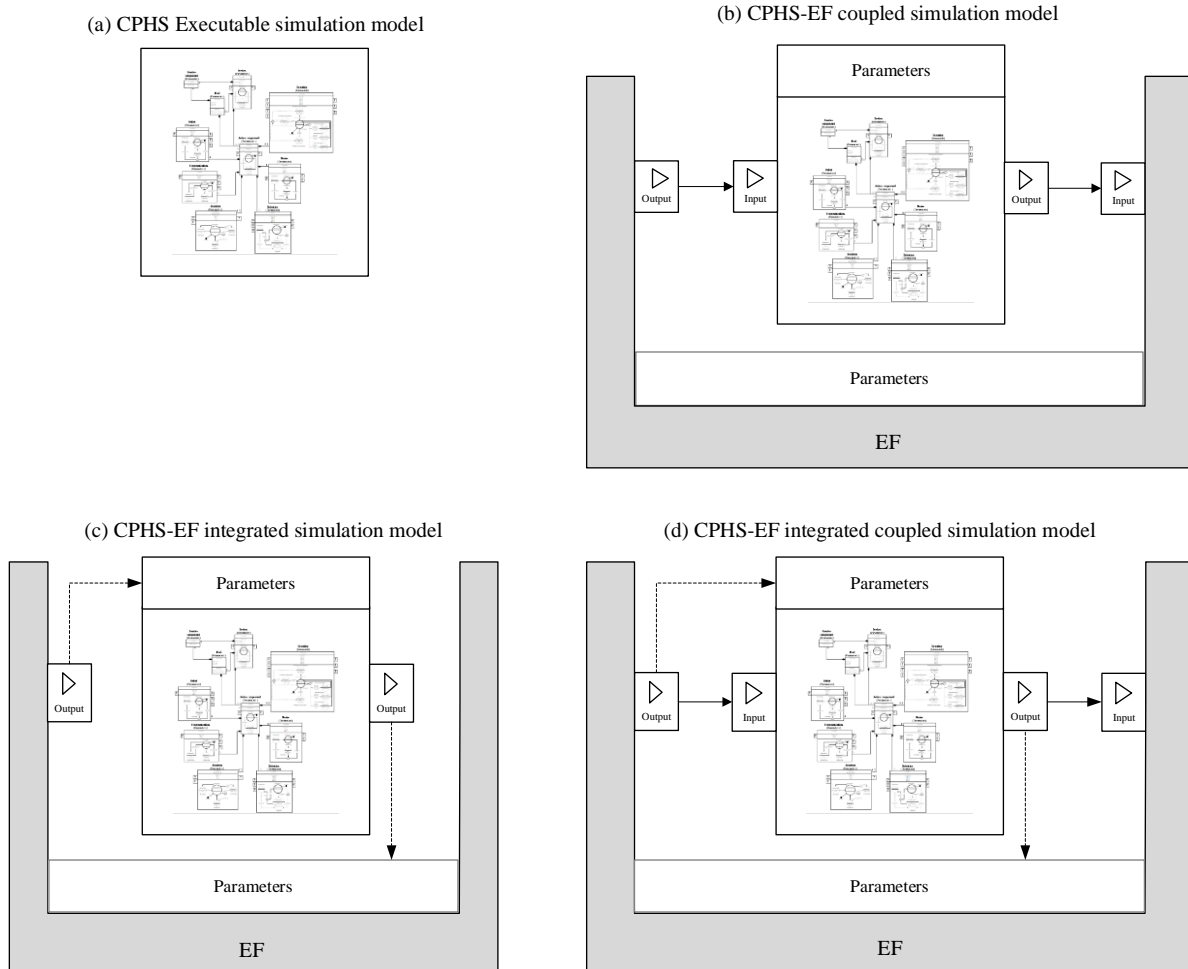
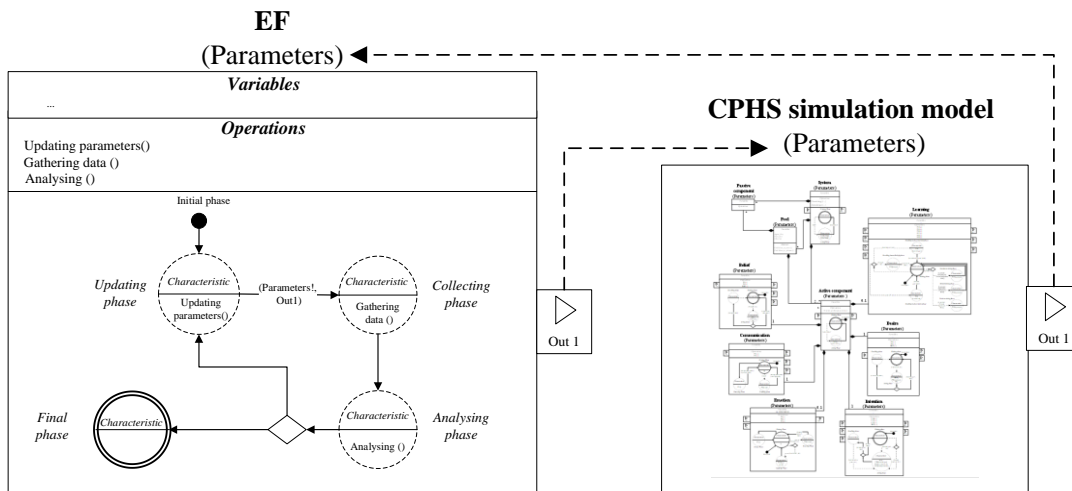


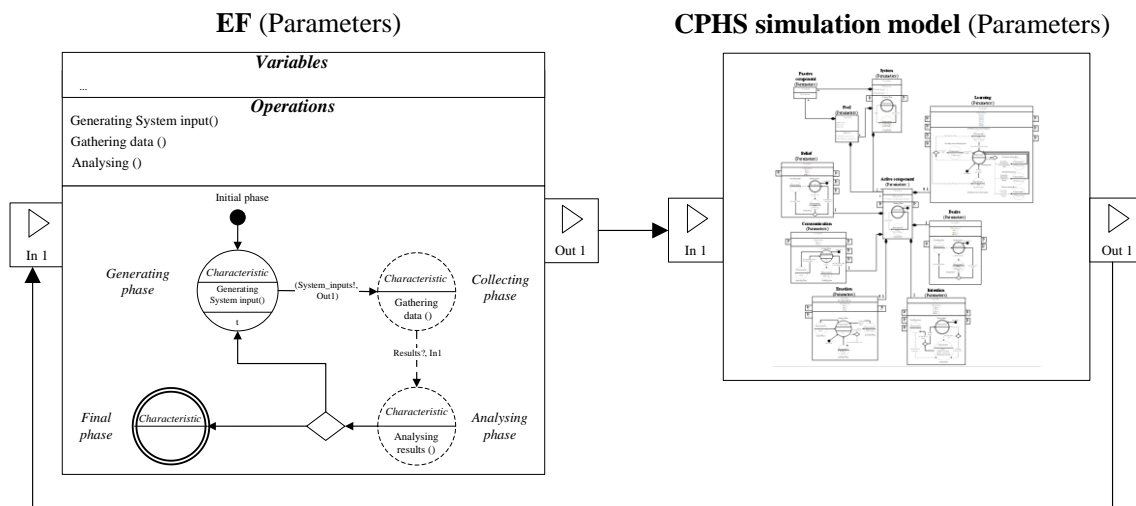
Figure 39 Available relationships between EF and CPHS simulation model

- *Updating phases:* Defining a family of values for parameters of the intended simulation model that should be experimented with.
- *Generating phase:* Generating discrete data in order to feed the system model.
- *Collecting phase:* Reading system critical data
- *Analysing phase:* Deciding what should be done with respect to the time, critical data, and results (if any)
- *Final phase:* Showing the end of M&S.

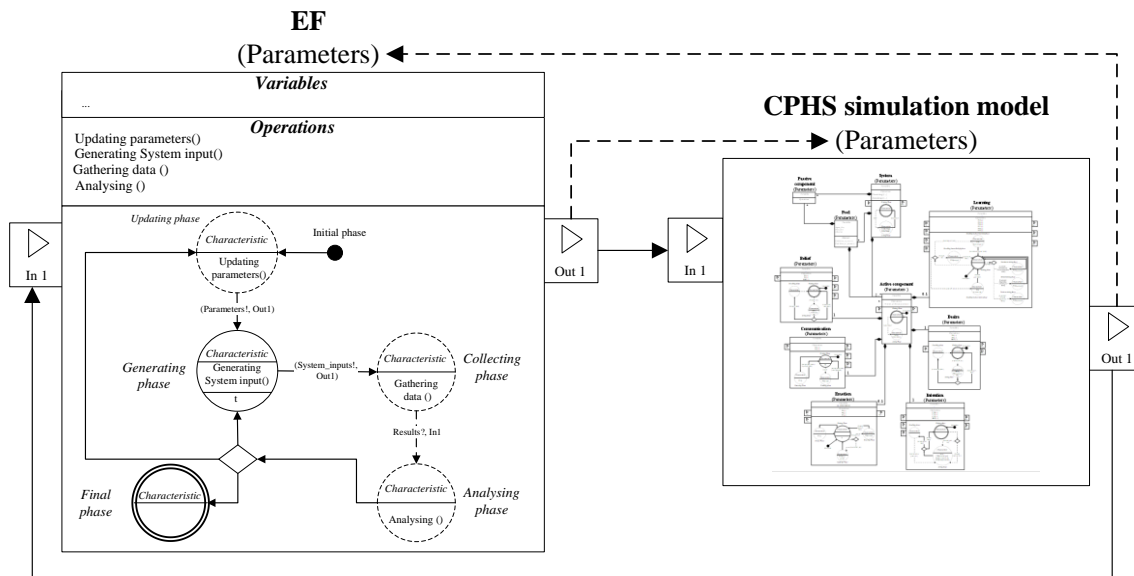
If we represent the EFs through the HiLLS model in Figure 39 and replace the system model with the GBCM, we will get to GECSM, as displayed in Figure 40.



(a) CPHS-EF integrated simulation model



(b) CPHS-EF coupled simulation model



(c) CPHS-EF integrated coupled simulation model

Figure 40 GECCM

### 3.4.1.2 Simulation relationship

The simulator is any computation software that executes the model to generate the behaviours (Seo & Kim, 2011) and perform the experiments on the simulated model. In this regard, a simulator should be able to execute the CPHS system model and its related EF. Since EF and CPHS system models are developed through HiLLS formalisms, it is necessary to demonstrate how HiLLS models can be executed via a simulator. The agent-based simulator has already been well-trodden in building simulation models of discrete entities (Salgado & Gilbert, 2013). There is no general instruction to make and execute the digital models because any simulation software has its own tools and technics. Using HiLLS to Anylogic transformation (see Table 8), we use AnyLogic as an agent-based simulator to model and execute HiLLS models.

### 3.4.2 GECM: Illustrative case

Once again, let's back up to the example of robotic surgery. We tend to run a simulation just for monitoring action (a5) as a subsystem of robotic surgery and test two scenarios for supervisor attention level. The first scenario is associated with a situation in which the supervisor watches the monitor on average every 2 seconds with a deviation of 0.5 seconds. In the second scenario, the time interval of watching follows a normal distribution with a mean of 3.5 and a deviation of 0.5 seconds. Regarding the M&S framework (see Figure 41), the monitoring action is the source system, and the context includes scenarios (supervisor attention levels) and assumptions (e.g., vital signs of the patient).

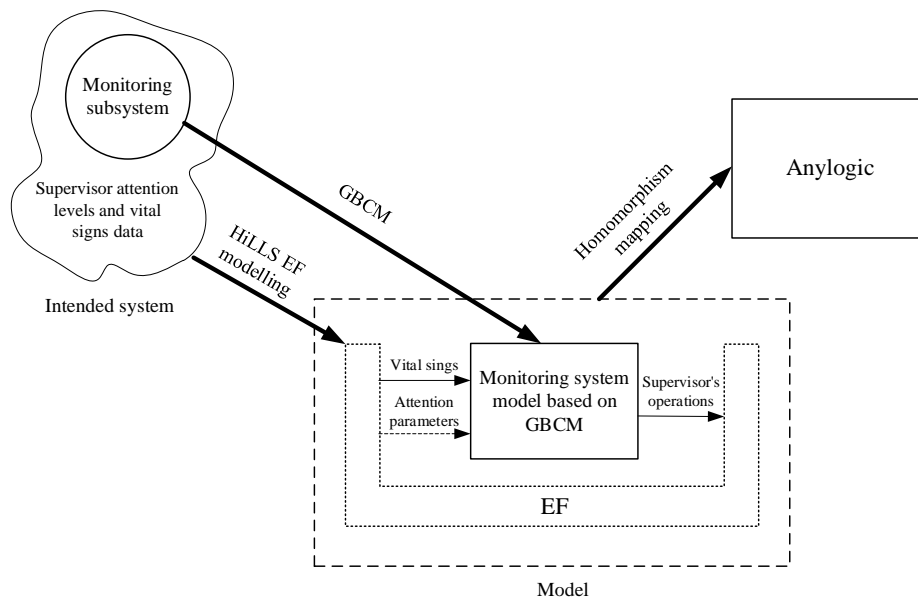


Figure 41 M&S framework for monitoring action

The system model is the monitoring action model based on GBCM that includes the supervisor and the monitor models. The monitor receives vital signs and displays the data to the supervisor, who watch the screen with probabilistic interval time. The supervisor analyses

data and decides what to do. If he detects a critical condition, he sends alert messages to the surgeon (out of model scope).

We can infer that the monitoring model interacts with its environment. EF models the context and environment by generating vital signs and attention level parameters and also receiving the supervisor's alerting messages. Accordingly, we deal with a CPHS-EF integrated coupled simulation model. According to the GBCM, the monitoring system should be modelled as an H-System with "connecting" and "initializing" functions to connect the ports of EF to the monitor model and the supervisor model to EF. Figure 42 (b) illustrates the monitoring system model developed via AnyLogic software. The behavioural models of the monitor and supervisor are given in Appendix B. Since EF interacts with the system model via inputs, outputs, and parameters, we deal with an integrated coupled simulation model. Figure 42 (a) shows the EF model in which updating function sets the attention level, the generating function creates vital signs data, the gathering function collects data for time plots, and the analysing function determines when the scenario is changed, and the simulation is terminated.

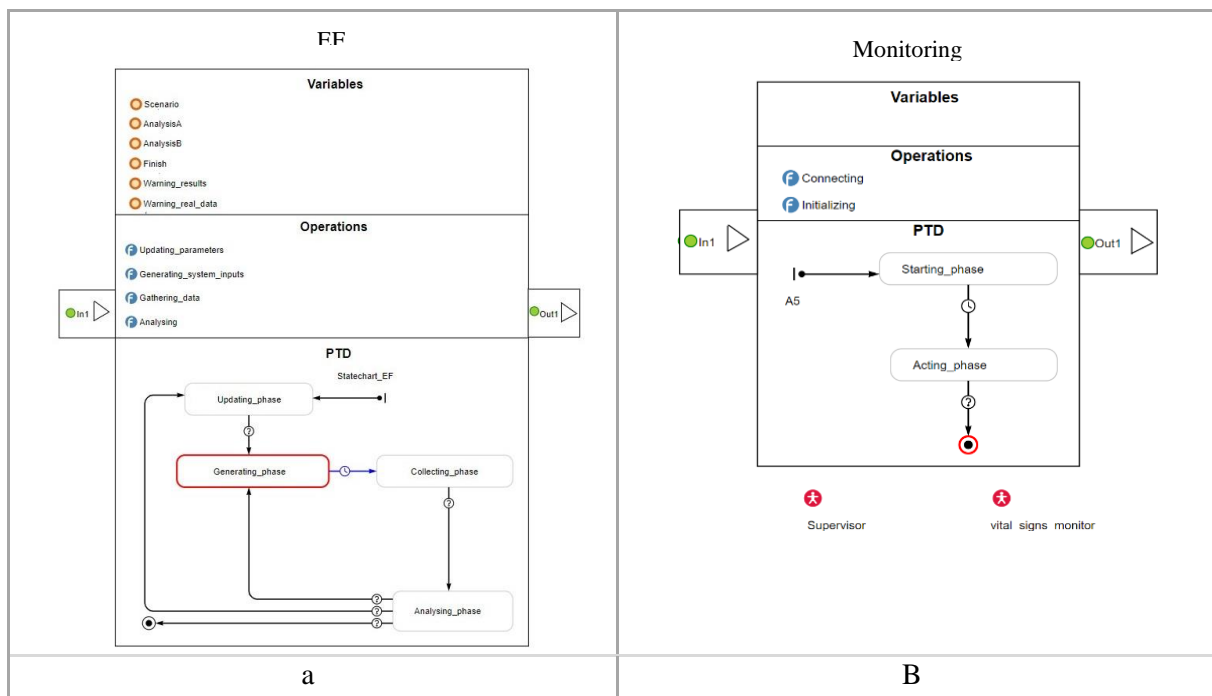


Figure 42 EF and system model

Once the simulation runs, the EF generates vital signs data and sends it to the system model every second. The generated data are demonstrated in Figure 43. The sent data is received and displayed by the model of the vital signs monitor. Observing and analysing the monitor, the supervisor decides whether to notify the surgeon or not. If it is so, the supervisor returns an alert to the EF. Figure 44 shows the warnings that should be announced ideally (required warning) and the warnings that have been announced by the supervisor model during simulation (supervisor warning). Comparing these two time-plots shows that the supervisor with attention level A only missed the opportunity to announce two critical conditions. While with attention level B, he has not announced four serious conditions.



Figure 43 Generated vital signs data in EF

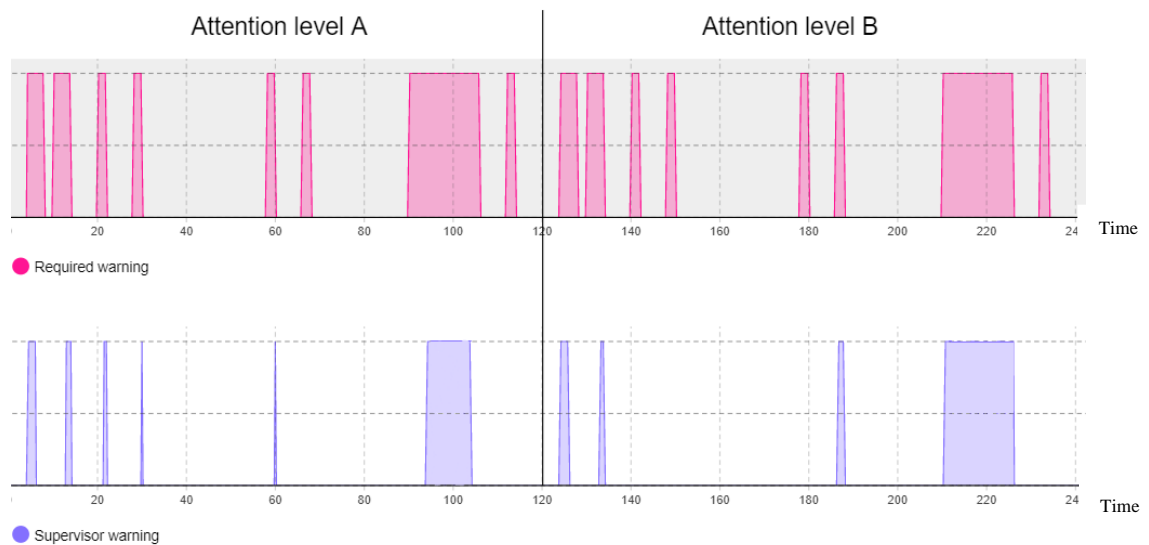


Figure 44 Simulation results for monitoring action produced by EF

### 3.4.3 ECL Summary

ECL addressed the M&S framework for CPHS based on system, model and simulator. GECM is the heart of ECL that connects the system to the model by GBCM and EF HiLLS modelling. The proposed GECM provided three generic executable models based on the relationship between EFs and GBCM. Since each simulator has its own tools, the relationship between the model and simulation is not included in our GECM. However, we used the HiLLS-AnyLogic transformation provided by Koita et al. (2022) (See Table 8) to show how a simulator i.e., AnyLogic can run EF and system models. Finally, an illustrative case showed how an execution-centric model could be developed using a behaviour-centric model.

## 3.5 Conclusion

This chapter revealed our contributions to the field of M&S for CPHS. The first contribution aimed to analyse CPHS and throw light on different angles of such a system for modellers. The reviewed descriptive frameworks either focused on the socio-technical aspect of CPHS and introduced very abstract concepts in the form of explanatory frameworks or emphasized new technologies and the nature of interactions within the system. But a suitable descriptive framework for modellers should not only explain the socio-technical nature, interactions and useful technologies of the CPHS but also be able to represent them in a unified architecture. Furthermore, this architecture should be translatable to existing modelling languages. Thus, firstly we discussed the key notions of CPHS regardless of the application domain and then put forward the GPCM on the basis of activity theory paradigms to assist modellers in understanding CPHS for M&S purposes. To the best of our knowledge, GPCM is the first model using activity theory principles to describe CPHS.

When the modellers understand the CPHS architecture, they need to know how to model the behaviour of the system components. As indicated in the literature review, most of the M&S frameworks of CPHS have been developed according to the CPS frameworks, which have not given adequate attention to human modelling and its complexity. This prompted us to propose a generic component behaviour architecture founded on the BDI model. To the extent of our knowledge, this is the first architecture that can model the behaviour of humans and tech tools (i.e., goal-directed, emotion-influenced, and learning and experience-based behaviours) in CPHS. By using GPCM and CBA, we provided the GBCM based on HiLLS formalism to make an executable model of CPHS. As far as we know, this is the first work that used HiLLS formalism to make a CPHS simulation model. With the CPHS simulation model in hand, modellers need execution infrastructures to run it and reach M&S objectives. As the third contribution, we provided the GECM in accordance with the SMS approach and HiLLS formalism and illustrated how a CPHS simulation model can be parameterised and launched in simulation software. As far as we can tell, GECM is the first execution model to parameterize and manage the implementation of CPHS simulation model.



## CHAPTER 4

# Case study: Intelligent Manufacturing System

### 4.1 Introduction

A case study is presented to demonstrate how our proposed framework can be used to model and simulate a CPHS. This case includes tech tools (autonomous robots and machines) and humans (operators) to bring about situations in which CPHS components exhibit emotion-influenced, learning-based, and goal-directed behaviours. It provides convincing evidence to ensure the effectiveness of our framework in modelling and simulating different behaviours within CPHS. In the following, we are going to introduce the intelligent manufacturing system as a case study for M&S.

### 4.2. Drone manufacturing system

An intelligent manufacturing system fabricates multi-rotor drones for aerial photography. The presentation of drone parts is available in Appendix C. Customers are able to apply their preferred features (drone size, battery, motor and camera). During manufacturing, the products (semi-finished and finished) are smart, which means that, from the initial stage, each product gets an RFID tag to communicate order ID (product ID) with the production system. Four

workstations with different resources (e.g., operators and robots) get involved in the production line. Figure 45 gives an overview of the production line.

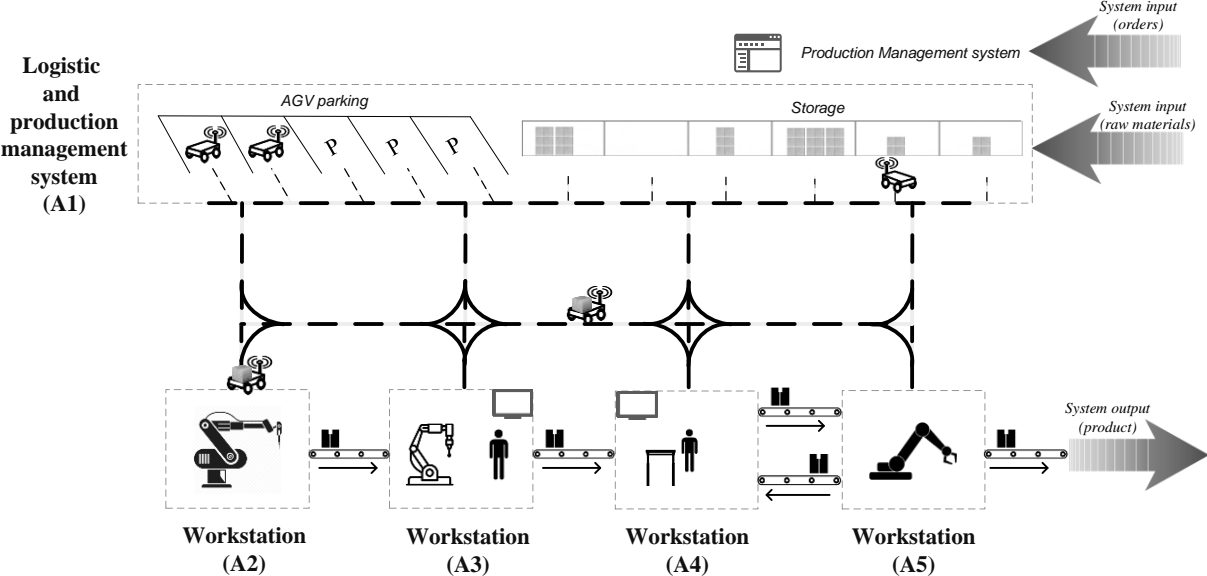


Figure 45 Overview of photography drone production line.

Production Management System takes customers’ orders, tracks and monitors the production, handles required materials, and manages AGVs which feed workstations with raw materials throughout the production line. All workstations are equipped with tag readers to communicate with RFID tags. They read and send the product ID to the production management system as soon as the product is received at the work station. In return, the system either displays corresponding product information on the screen or sends the required information to the robots.

The descriptions of the workstations are given in the following:

**Workstation A2:** The autonomous robot receives the required information from the production management system and raw materials from AGVs. Raw materials in this workstation are composed of a frame and an RFID tag. According to the frame size, the raw frame must be cut, and then an RFID must be attached to the back. Finally, the semi-finished product is put on a conveyor belt. The autonomous robot will be replaced by a new intelligent robot equipped with a Predictive Maintenance Module. This module can predict the failure of the robot based on historical data and put the robot in inactive mode, and call the maintenance specialist to take the necessary action. For this purpose, firstly, the module collects the health data (e.g., temperature and vibration) and the state of the robot (Broken/Active) during a certain period of time (training period) in order to train a learning algorithm that is based on feedforward artificial neural network model (multilayer perceptron). Once the algorithm is well trained, the module can predict failures before they occur (calling period). Suppose that the

module has predicted a failure. In this case, the module will put the robot in inactive mode, and a maintenance specialist will be called in to take the necessary actions. In this case, the maintenance operation time will be a normal distribution with a mean of 6 and a deviation of 2. Whereas, in the event of an unpredicted failure, it takes about 20 minutes (a normal distribution with a mean of 20 and a standard deviation of 3) to fix it.

**Workstation A3:** Semi-product and raw materials are received at the workstation. When the robot gets the necessary information from the production system, it begins to install the circuit board on the frame. Next, the operator places the battery. The robot has the level of awareness to cooperate with the operator to ensure safety. Accordingly, it is able to recognize the action that the operator performs. Once the robot detects that the operator properly installs the battery, it connects the arms to the frame. Then the operator installs the motors on the arms and puts the semi-finished product on a conveyor. During the operations, the necessary information is displayed on the screen.

**Workstation A4:** In this work station, the process is started when the semi-product and raw materials are received. The operator picks up the raw materials delivered by AGVs. It should be noted that the AGVs are not allowed to approach the operator closer than 0.5 meters. The technical and safety information is shown on the screen. Using information, the operator begins to install the shells (up and down) and camera and then puts the semi-finished product on a conveyor. If the operator does not install the shells properly or they are defective, the drone will be returned to be fixed. This is a stressor event affecting the operator's work speed. If the task is performed correctly, the operator's stress is decayed over time, and the work speed will go back to the normal rhythm after a period of time.

**Workstation A5:** At this workstation, an autonomous robot receives raw materials and the semi-finished product and then checks the shells. If it is ok, the robot installs the bases and propellers according to the received information from the Production Management system and places the finished product on the conveyor. If the shells are not installed properly, the semi-finished product returns to workstation A4 for reworking.

### 4.3 M&S objectives

The purpose of this M&S is twofold. The first objective is to perform a what-if analysis to see the effects of replacing the existing robot with the new one (with learning-based behaviour) in the manufacturing system. The second objective is to provide insight into the emotion-influenced behaviour of the operator and determine how and to what extent defective products can affect the operator's performance.

## 4.2 Purpose-Centric Model

The first step is to analyse the system according to the GPCM. To do so, we need to determine the actions of the CPPS and identify components, requirements, and operations. We considered five main actions (four manufacturing and one supporting process) for the presented CPPS and denoted them with  $\{A_i \mid i \in \text{actions}\}$ . The required operations of each action were specified in the form of receiving EMPI, analysing, decision-making, and executive operations and denoted by  $\{A_{ij} \mid i \in \text{actions} \ j \in \text{operations}\}$ . Then, we identified all the components of the CPPS (i.e., active and passive ones.) and applicable rules and regulations (i.e., safety and technical requirements). Figure 46 gives an overview of the Purpose-Centric model of the CPPS.

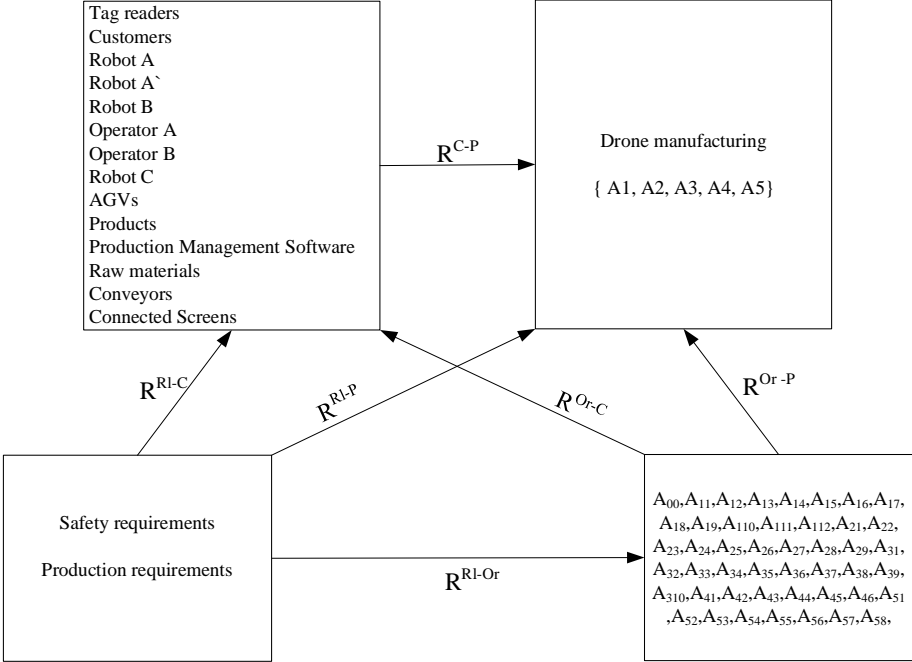


Figure 46 Purpose-Centric Model for the presented CPPS

We should develop the SysML requirement diagram, block diagrams and BPMN diagram to describe the constraints on the system, describe the components (e.g., relationships and properties and requirements), and represent the flow of the operations and their constraints. The diagrams are presented briefly in Appendix D for interested readers.

## 4.3 Behaviour-Centric Model

Once the purpose-centric model is well developed, we start to build the simulation model. Since the presented CPPS is an open system, our provided simulation model should interact with its environment by receiving inputs (Orders, raw materials) and sending outputs (products). The simulation model includes eleven H-Systems (active components) and three H-

Classes (passive components). The behaviour of active components has been modelled through different behavioural patterns. We used the goal-directed behavioural pattern (e.g., to model the behaviour of robot A), learning-based behavioural pattern (to model the behaviour of robot A') and the emotional-based behavioural pattern (to model the behaviour of operator B). All the operations identified in the BPMN diagram have been developed inside the intended behavioural constituents of components.

We give our simplified view of provided CPPS simulation model in Figure 47. Each H-System contains behavioural components that are shown as an example for Robot A` H-System. As an example, we discuss in detail the simulation model of Robot A`.

*Central active component:* This H-system has two parameters: Robot status and behavioural pattern. The modeller should initialise the behavioural pattern parameter by sending a message. Once the initialisation message is received, provided that the robot is in the active state, the H-System moves to the active phase executing the set\_up function (initialisation), which connects the ports of behavioural constituents in a way that the desired behavioural pattern is formed.

*Communication behavioural constituent:* As can be perceived from the diagrams of PCM, the robot receives raw materials (A22) as well as order specification (A21) and health data (A26). Thus, we considered three input ports to receive the related messages. When the communication H-System gets an event (message), provided that the robot is in the active state, it goes to the acting phase to execute a function (F1), which interprets incoming events and returns a new percept or learning percept (L-percepts). The percepts and L-percepts are sent through two ports which transfer them into input ports of Belief and Learning H-Systems, respectively.

*Belief behavioural constituent:* Since the robot does not analyse data, the inputs and outputs of the Belief H-System are the same, which means that the final beliefs are equal to percepts. In other words, the Belief H-System just temporarily stores some necessary data (e.g., order ID) and sends the received percepts as final beliefs via its output port to the input port of the Desire H-System.

*Desire behavioural constituent:* Once the final belief is received, a transition is fired that moves the H-System to the acting phase to execute a function (F8). This function determines the robot's goal (A23) according to the final beliefs and puts it in a variable. The selected goal can be: (Cutting S-Frame, attaching RFID tag, putting semi-product on a conveyor belt), (Cutting M-Frame, attaching RFID tag, putting semi-product on a conveyor belt), and (Cutting L-Frame, attaching RFID tag, putting semi-product on a conveyor belt). A Basic Reactive Plan (BRP) determines in which situation the robot uses its learning mechanism. If it is not intended to use

learning, the H-System sends the selected goal directly to the Intention H-System via the output port and returns to the waiting phase. Otherwise, BRP fires a transition that executes a function (F9) and moves the H-system to the recalling phase. Actually, F9 sends final beliefs to the Learning H-System.

*Intention behavioural constituent:* Initially, the H-System is in the waiting phase. As soon as a selected goal is received, the H-System moves to the selecting phase. In this phase, a function (F10) is executed to identify an action plan according to the selected goal and determine how long its execution will take. Since the robot has only one way to do its operations, the selected goal is equivalent to the action plan. Thus, F10 sets just the required time for the action plan ( $t_a$ ). Then, the H-System goes to the execution active phase, in which the system remains for a certain period of time ( $t_a$ ), and a function (F13) is executed. If the action plan is to “put the robot in inactive mode”, F13 will change the robot status parameter to inactive mode (A28) and execute the operation of calling maintenance specialist (A29), else, F13 first reads the order number from the belief H-System, and next, the operation (A24) is performed on the ordered product. Finally, the product is placed on the conveyor by performing operation A25. When all operations are performed successfully, the product will be sent to the next destination by an output port, and the H-System returns to the waiting phase. During operations (A24), the robot may crash. In this case, the defined methods are cancelled, and an emergency action plan, "calling the maintenance specialist (A29)," is executed, which turns the robot status of central H-System to “Broken” mode and sends a message via an output port.

In robot A`, whenever the action plan is executed (either normal or emergency), the temperature and vibration parameters and the state of the robot (broken/active) are sent to the communication H-System as health data (self-feedback), which provides an L-percept to the system.

*Learning behavioural constituent:* This behavioural constituent uses L-percepts to train learning algorithms. To do so, when the H-System gets L-percept through its input port, the H-System moves to the desire training phase to execute the training function (F16). As mentioned earlier, L-percept consists of information regarding temperature, vibration and the state of the robot.

CPPS model for simulation ( \_ )

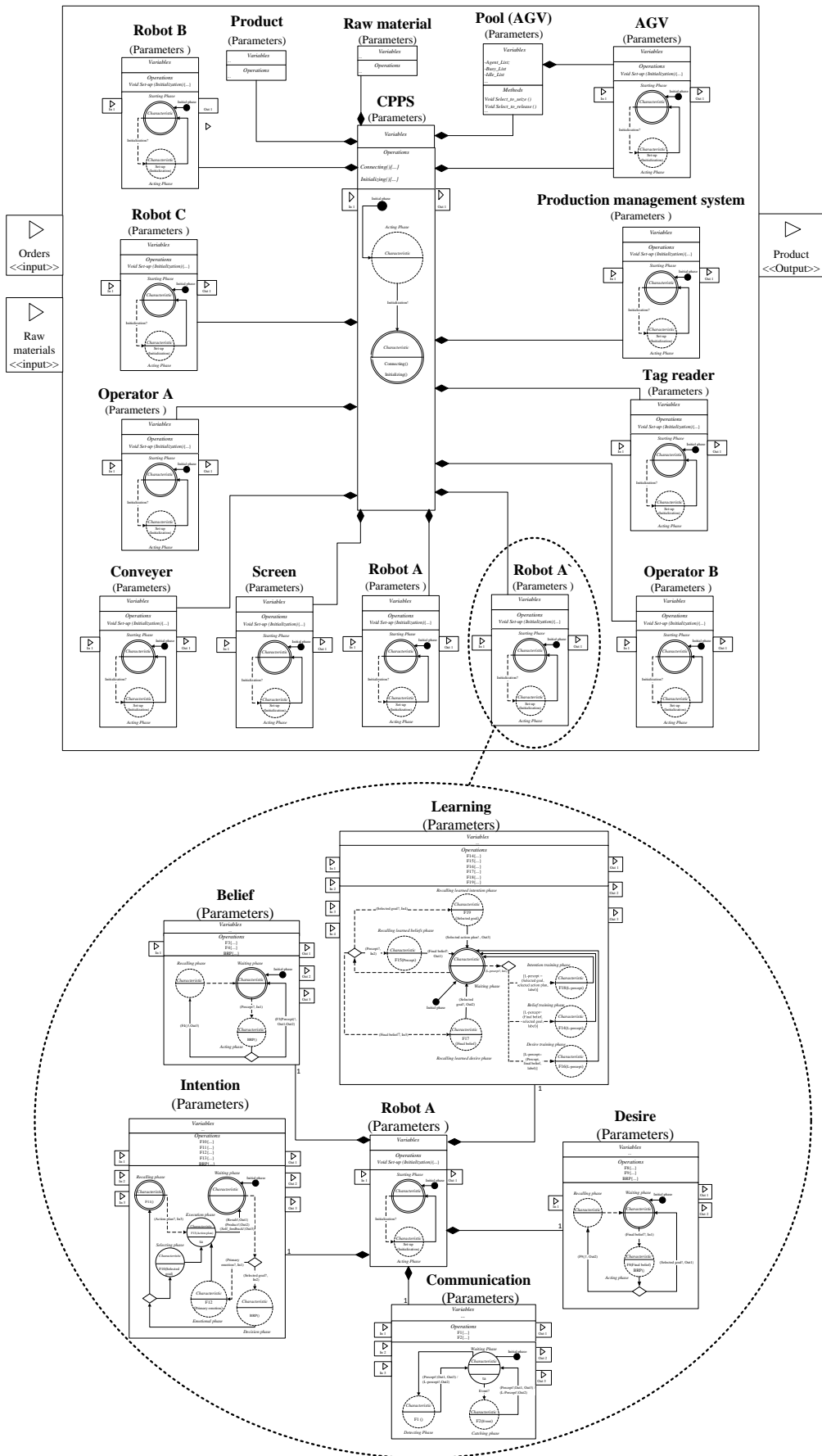


Figure 47 Overview of CPPS simulation model based on GBCM

As previously noted, robot A` should predict failures before occurrence. Thus, when the robot needs to use its learning mechanism, i.e., H-System receives the final belief as input, the H-system goes to the recalling phase, reads the values of temperature and vibration parameters and runs the learning algorithm (F17) that defines a goal for the robot (should be inactive or not). Suppose the learning algorithm shows that failure will occur. In that case, the selected goal, calling the maintenance specialist, will be sent to the intended H-System through the output port. Else, it sends the selected goal, which is already determined by the desire H-System, to the intention H-System.

Once the models of all the CPPS components are developed, it is time to associate the active components of the system with each other and with the environment. This is done by the CPPS H-System, which relates different components by connecting their output ports of intention H-Systems to input ports of communication H-Systems. For example, robot A should be connected to the conveyor in order to transfer a semi-finished product to the conveyor belt. To do so, CPPS H-System executes a function (connecting) that connects RobotA.Intention.out1 to Convoyer.Communication.In.1. Due to this action, once a semi-finished product is manufactured by robot A, it is transferred to the conveyor belt.

### 4.4 Execution-Centric model

The presented simulation model should be implemented in such a way that the objectives of M&S is achieved. We develop the M&S Framework as shown in Figure 48.

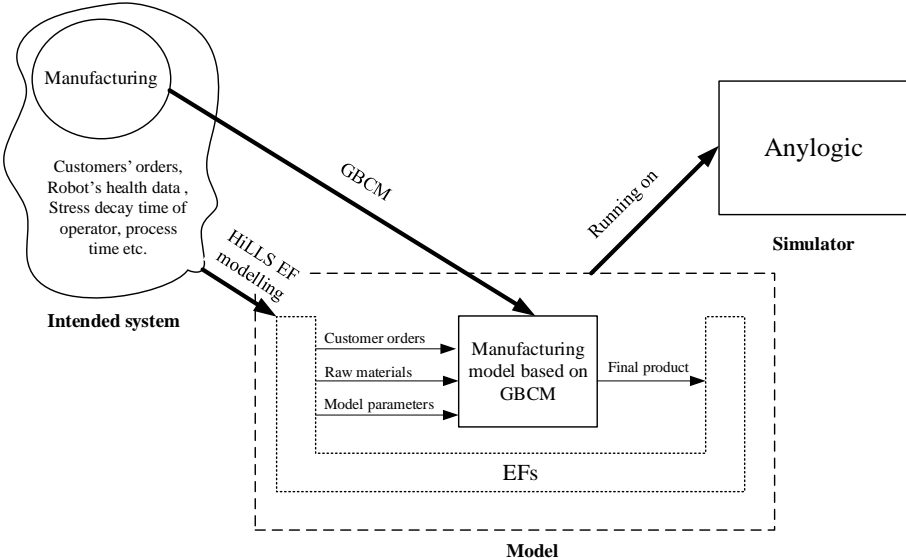


Figure 48 Overview of M&S Framework for CPPS

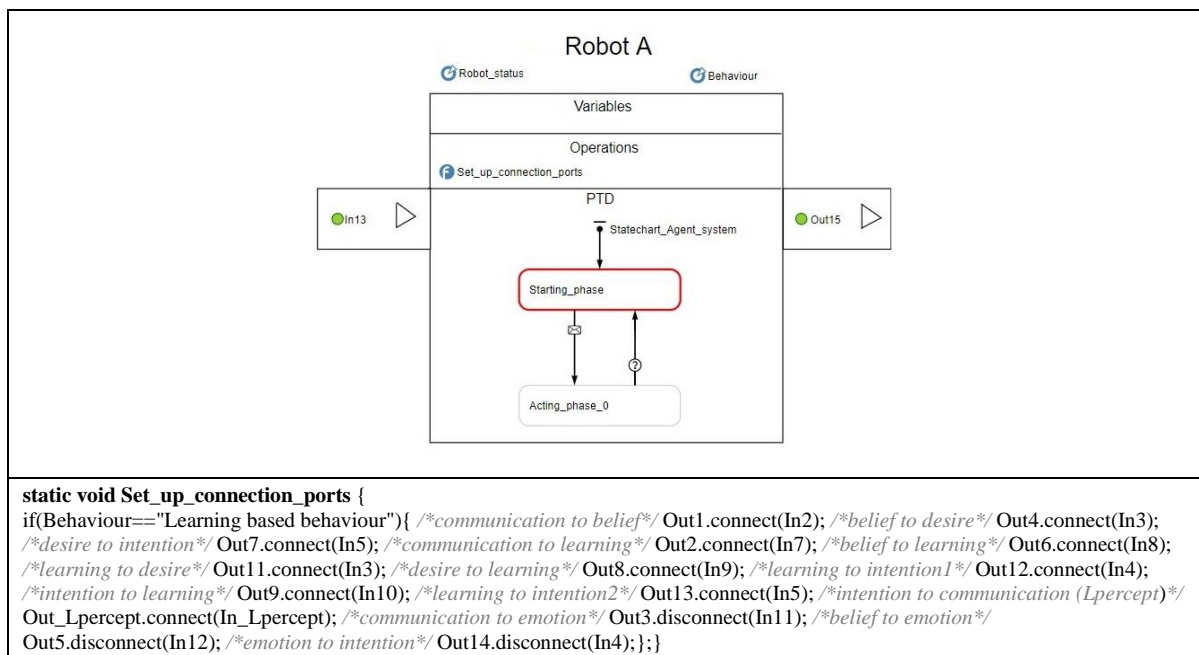
By this stage, the simulation model and the required EFs should be developed and connected to the CPPS simulation model. given that EFs generate input data for the CPPS Simulation



model, set some parameter values, and finally receive the simulation model's output, the relation between the CPPS model and EF should be deemed as an integrated coupled relationship. Once EFs and CPPS are well-modelled through HiLLS formalism, they should be converted to the AnyLogic simulation models. Since it is not possible to explain all the developed models in AnyLogic here, we give explanations of the robot A` simulation model and its related EF.

***The representation of robot A` simulation model in Anylogic:***

All the H-Systems and H-Classes of robot A` are developed as agents. We begin with the Central H-System, which should connect the ports of the behavioural constituents as previously explained. Figure 49 illustrates the central agent of robot A` and its set up function.



*Figure 49 Central agent of Robot A (AnyLogic illustration)*

In the next step, we developed the communication agent. According to the communication H-System, three input ports are considered for this agent. Figure 50 shows the communication agent and how one of the input ports acts upon receiving raw materials (agent) and fires an event in the state chart. Finally, the F1 function sends information via the agent output ports.

Percepts are received in the input ports of the Belief agent. As previously mentioned, this agent just keeps the order number temporarily in a variable and forwards percept as a final belief to the Desire agent. When Desire agent receives the final belief, the BRP parameter can launch two mechanisms in the agent. The first is that the agent selects a goal (F8) and sends it to the Intention agent. The second is determining the goal and moving to the recalling phase in which F9 is executed. This function sends the selected goal and received beliefs to the learning agent. In other words, the BRP parameter determines whether the robot should use

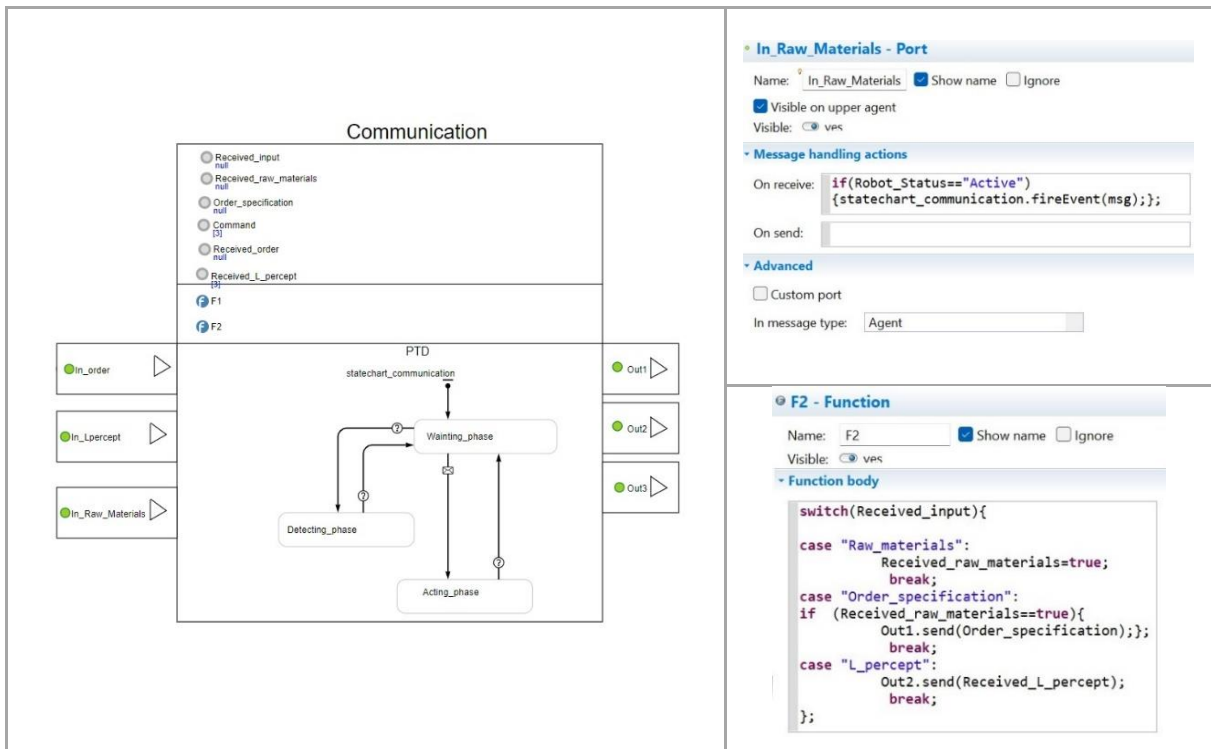


Figure 50 Communication agent of Robot A (AnyLogic illustration)

learning to select a goal or not. EF agents must define the value of the BRP parameter. Figure 51 depicts the Belief and Desire agents as well as F9.

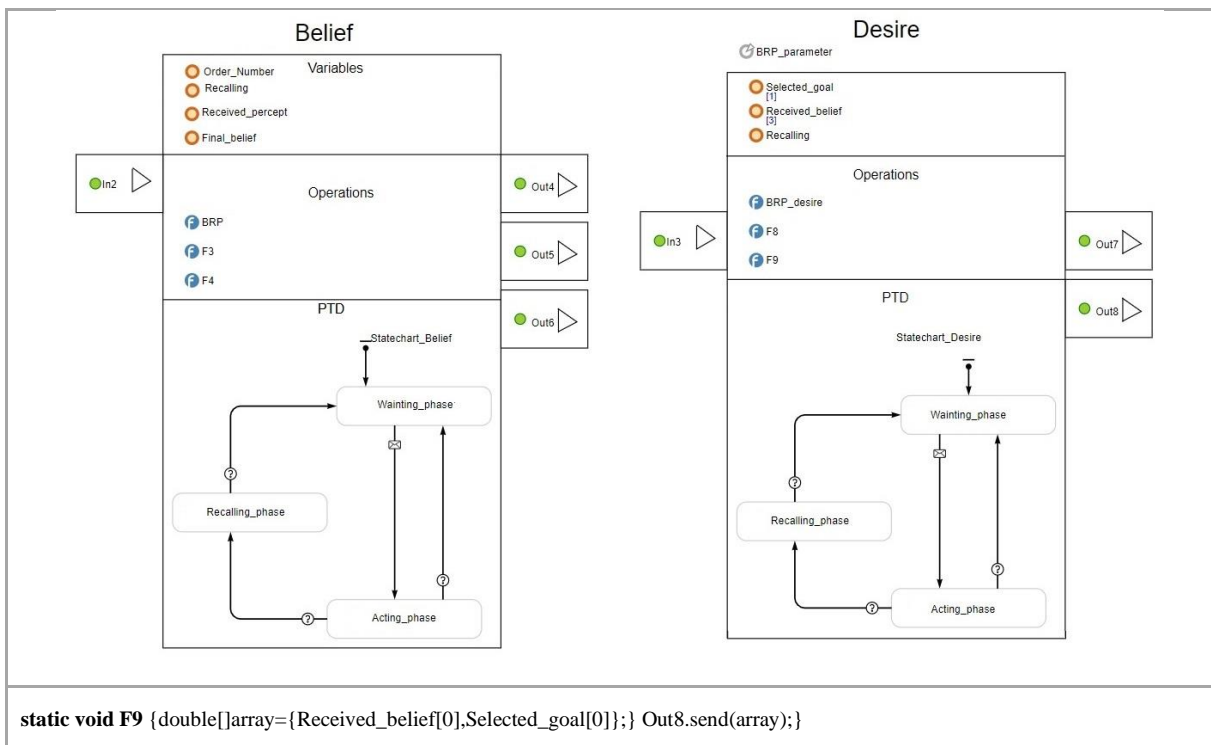


Figure 51 Belief and Desire agents of Robot A (AnyLogic illustration)

The Intention agent sets the action plan (F10) and runs the executive actions (F13). Since the robot does not use the learning process to call the action plan and does not have emotional behaviour, its state chart will not be moved to the recall and emotion phases. In

Figure 52, we

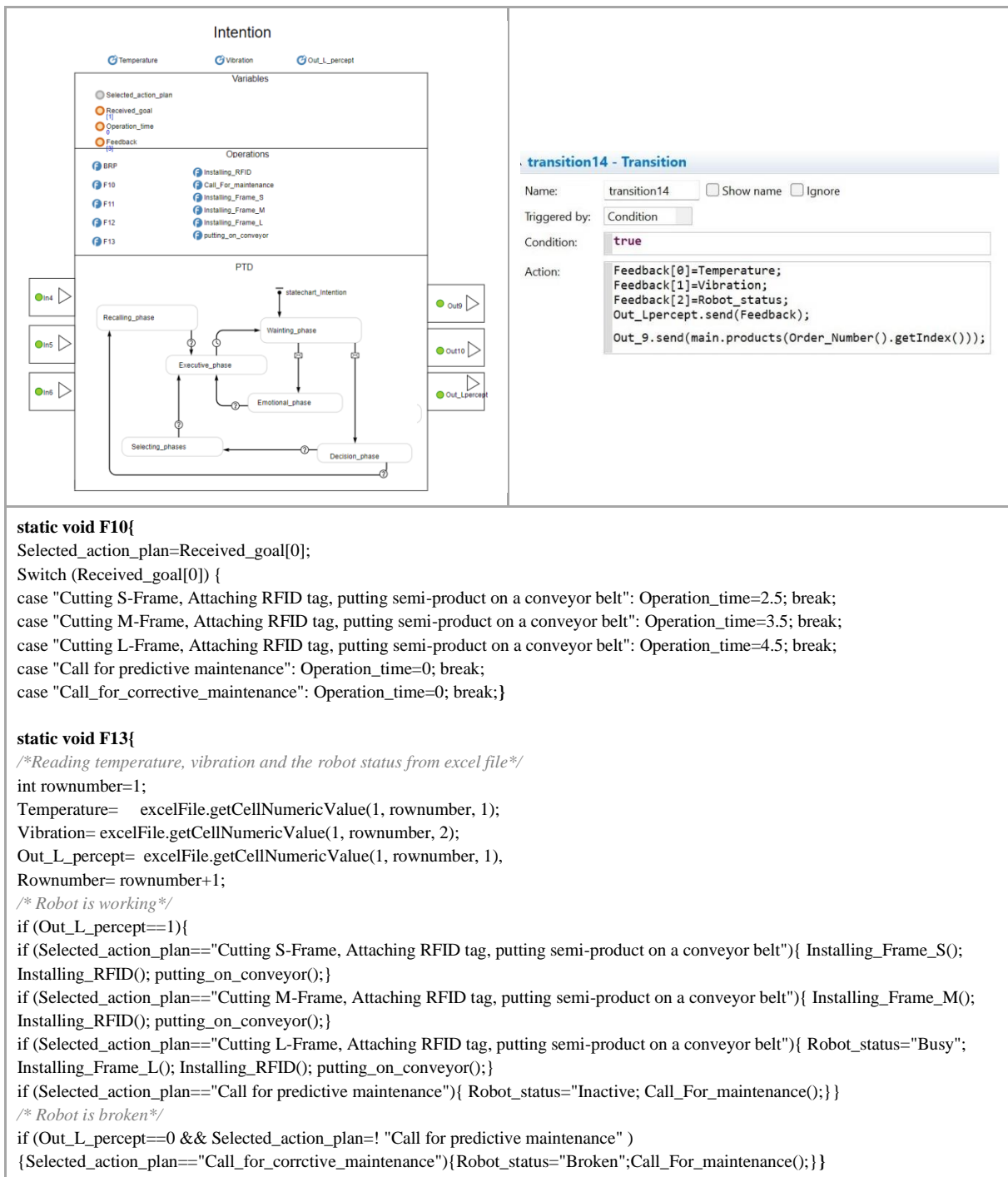


Figure 52 Intention agent of Robot A (AnyLogic illustration)

illustrate the intention agent, the functions and the final transition which sends out the results.

As previously discussed, the learning agent can receive L-percepts (to train the algorithm) and requests (to use the algorithm and return an output). We use a learning mechanism to improve the decision-making of the robot (desire agent). Thus, we define the functions of F16 and F17 inside the training desire and recalling desire phases, respectively. In these functions, we used Neuroph Studio, an open-source Java library with basic classes corresponding to neural

network concepts. We chose Sigmond for the transfer function and Backpropagation with momentum for the learning rule in our neural network. For NN training, the max error parameter must be defined by the EF agent. During training, when the value drops below the max error, it means that the training is completed.

Figure 53 demonstrates Learning agent and shows how we used Neuroph Studio java classes to train and use NN.

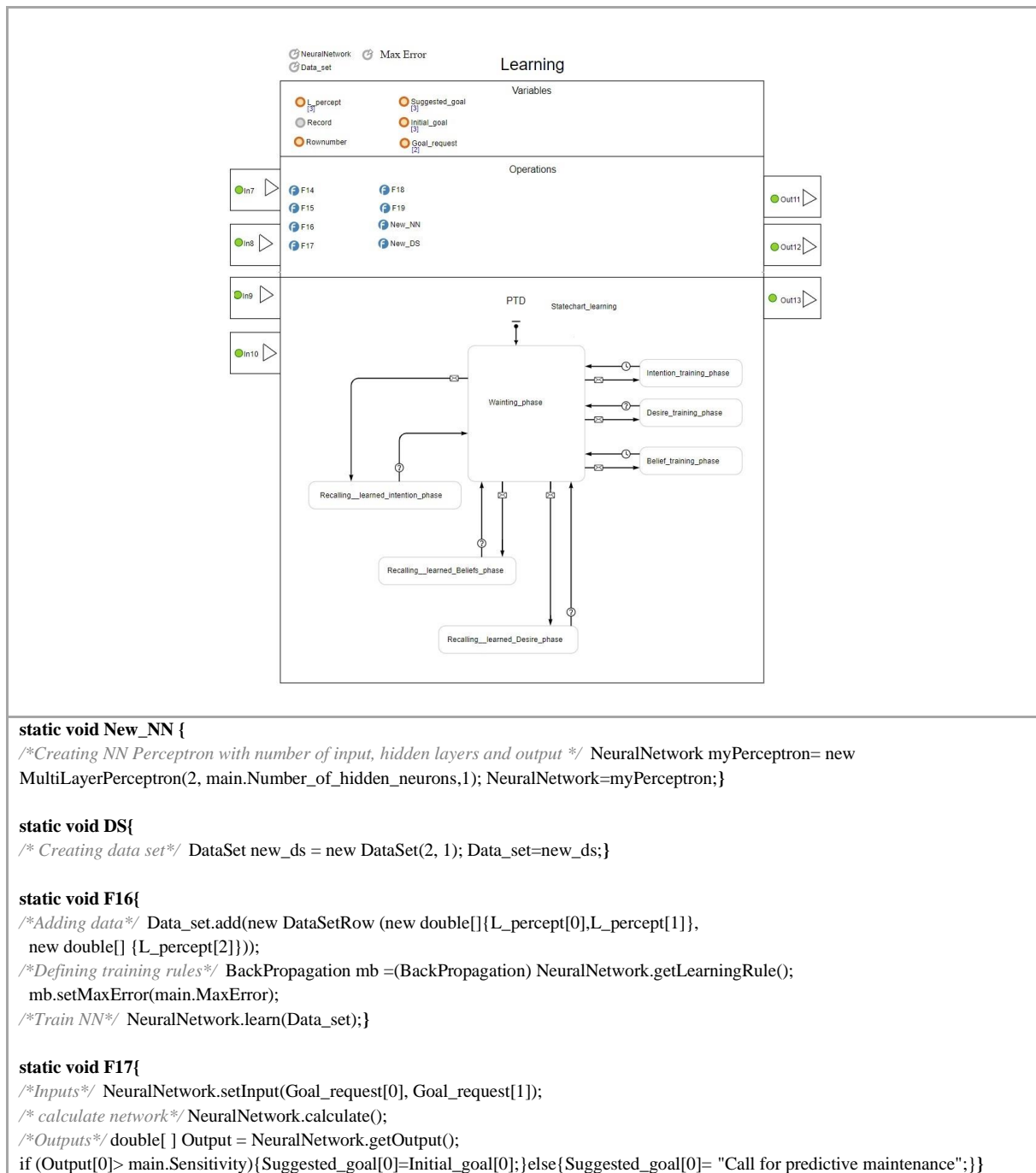


Figure 53 Learning agent of Robot A (AnyLogic illustration)

### *The representation of EF in Anylogic:*

A specific EF was developed for the robot to provide inputs and values of parameters for the robot model, collect desired data and demonstrate the results by indicators. We developed a user interface to facilitate defining inputs in updating phase and a graphical view to represent diagrammatic indicators in analysing phase. The EF and user interface are shown in Figure 54. We initialised the EF by means of the user interface and ran the simulation.

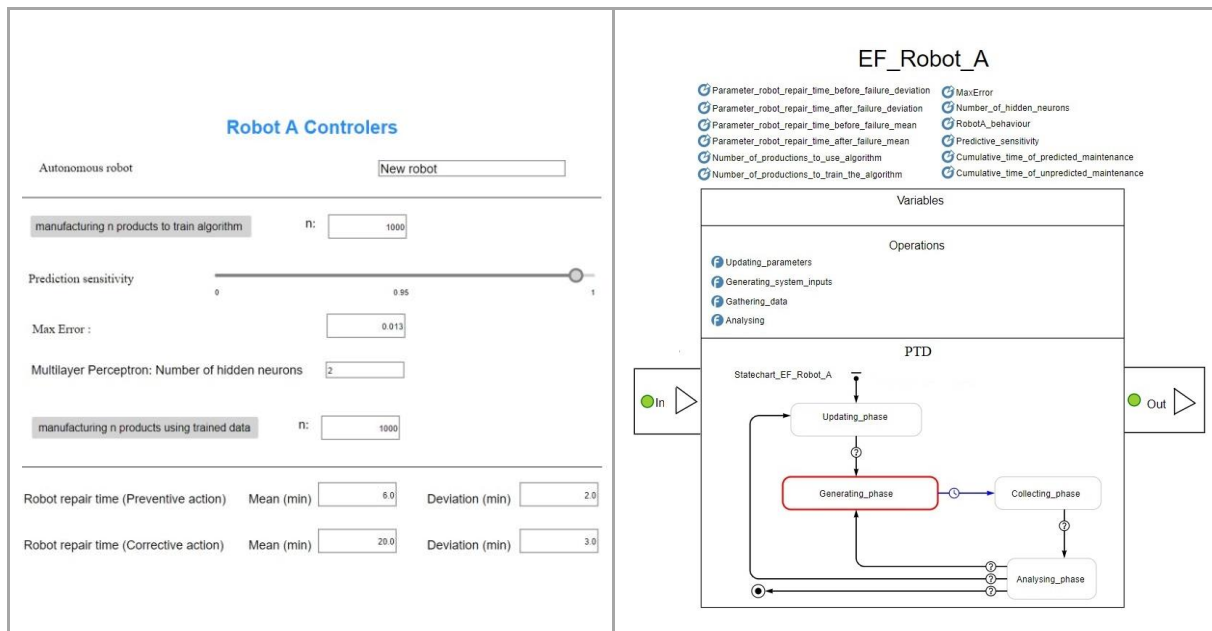


Figure 54. EF agent and controllers for Robot A' (AnyLogic illustration)

Figure 55 depicts the simulation result when the robot trains the learning algorithm. It is apparent from Figure 55 that 13 failures occurred during the production of one thousand products and consequently, 13 corrective maintenance was performed. The repair of these failures took a total of 251 minutes. The time distribution of failures can be seen in the time plot.

In manufacturing the next thousand products, the robot uses its learning algorithm. From Figure 56, we can see that 16 maintenance (9 predicted maintenance and 7 corrective maintenance) have been done. Although the number of maintenances was higher than before (16 vs 13), the total maintenance time dropped to 193 minutes (138 min predicted maintenance and 55 min corrective maintenance). The prediction success is about 56%, an indicator of the learning algorithm's performance.

In the same way as intelligent robot modelling, we were able to model the behaviour of operator B. The differences lie in their behavioural pattern (i.e., emotion-based behaviour instead of learning-based behaviour), internal functions (e.g., F1) and variables and parameters (e.g., stress). Appendix E illustrates the Anylogic simulation model of operator B. We

developed EF and Controllers for Operator B as we did for the intelligent robot. Figure 57 shows the EF agent and controllers for Operator B.

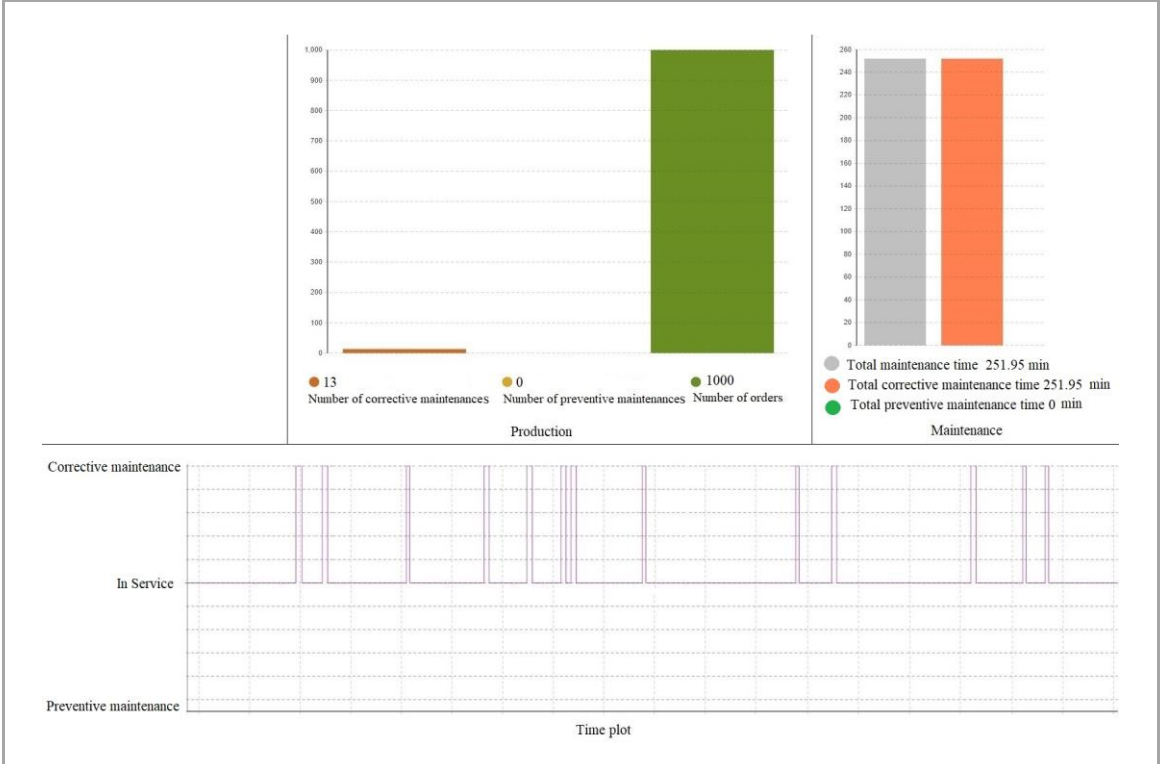


Figure 55 Robot simulation results (during training)

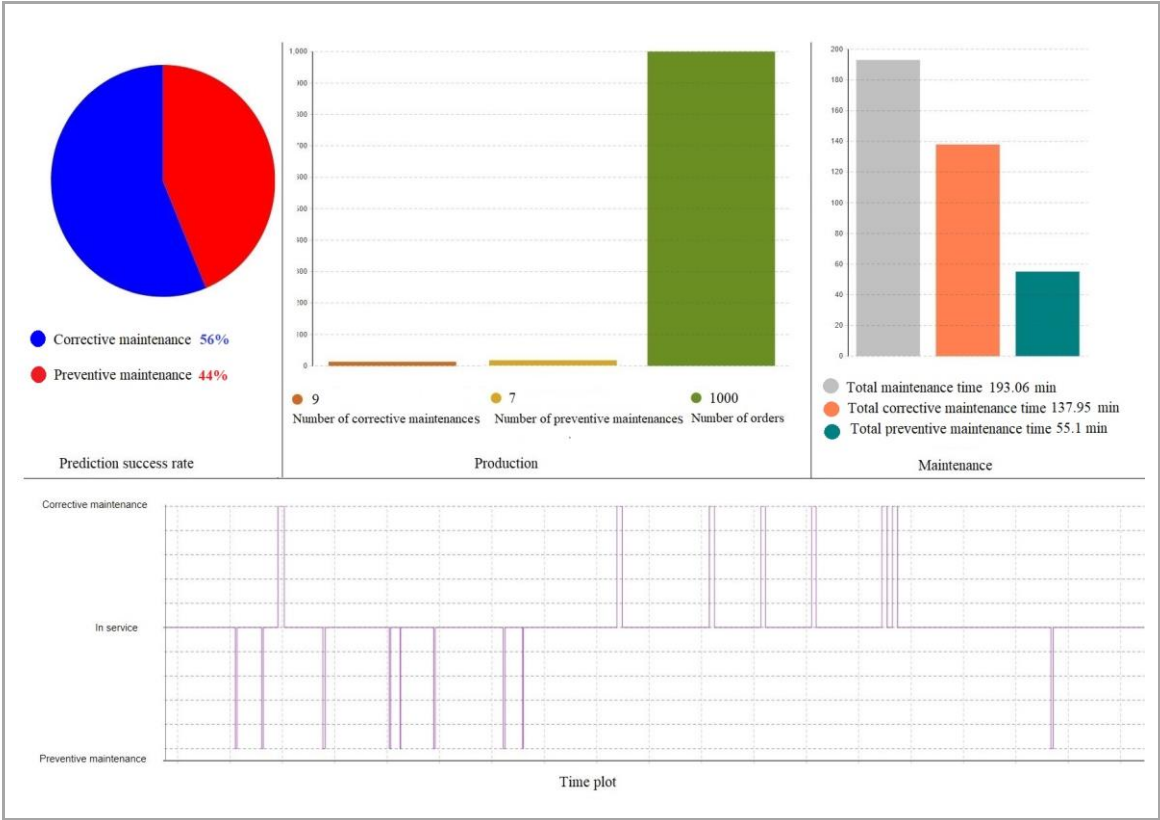


Figure 56 Robot simulation results (during testing)

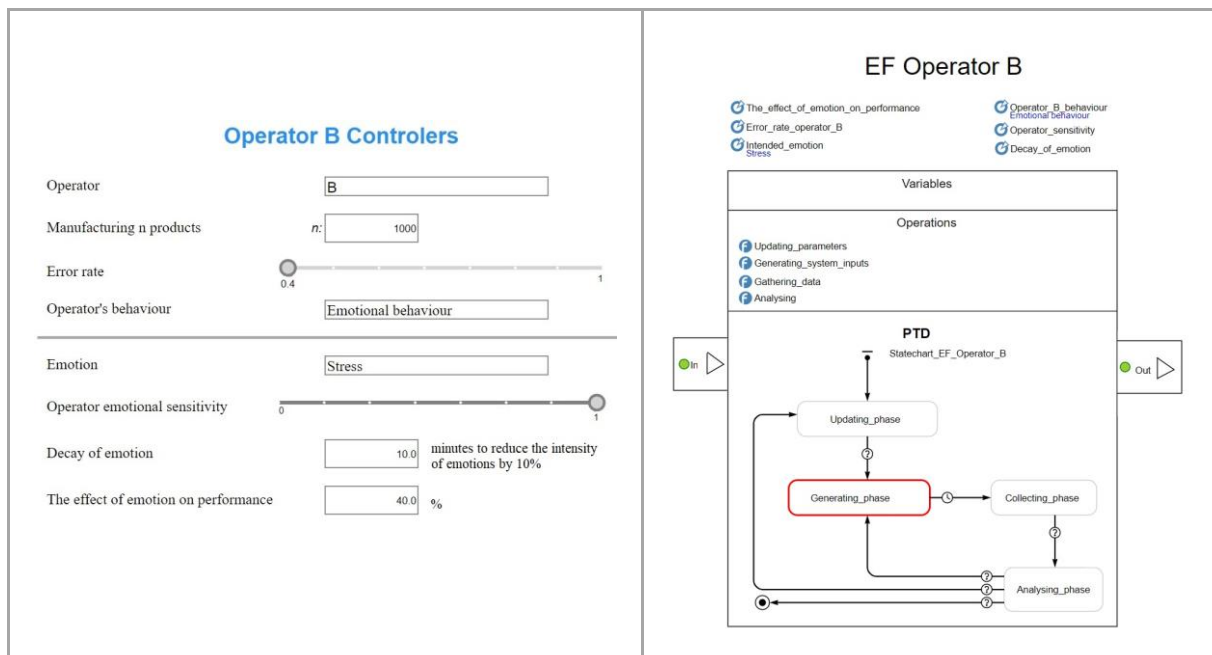


Figure 57 EF agent and controllers for Operator B (AnyLogic illustration)

We defined three controllers as operator emotional sensitivity, the effect of emotion on performance and error rate. The emotional sensitivity of the operator indicates the likelihood of considering the stimulus. In other words, the possibility of getting stressed when receiving the returned product. Error rate shows the probability of fabricating a defective product by the operator. The controller of emotion effect on performance was developed to enable M&S users to define to what extent stress affects the operator's process time. We calculated the assembling process time under stress as follows in the Intention agent during simulation:

Process time (stress mode) = process time (normal mode) × emotion effect % × emotion intensity %

Figure 58 is the simulation result when the operator produces 500 products without error (error rate = 0). In the second scenario, the probability of making a defective product by the operator is 5%. The operator's stress will be maximum if he has to rework (receive the returned product). Stress affects his performance by 80%. However, every ten minutes (decay time), 10% of his stress intensity decreases. Figure 59 shows the results of the second scenario. In the third scenario (See Figure 60), the probability of making a defective product is 6%. Nevertheless, stress affects the operator's performance by 40%, and the decay time is two minutes. By comparing the results of the operator's total working time in three scenarios, we find out to what extent the emotion decay time, the percentage of emotion's impact on performance and the operator's error rate affect the total production time of this workstation.



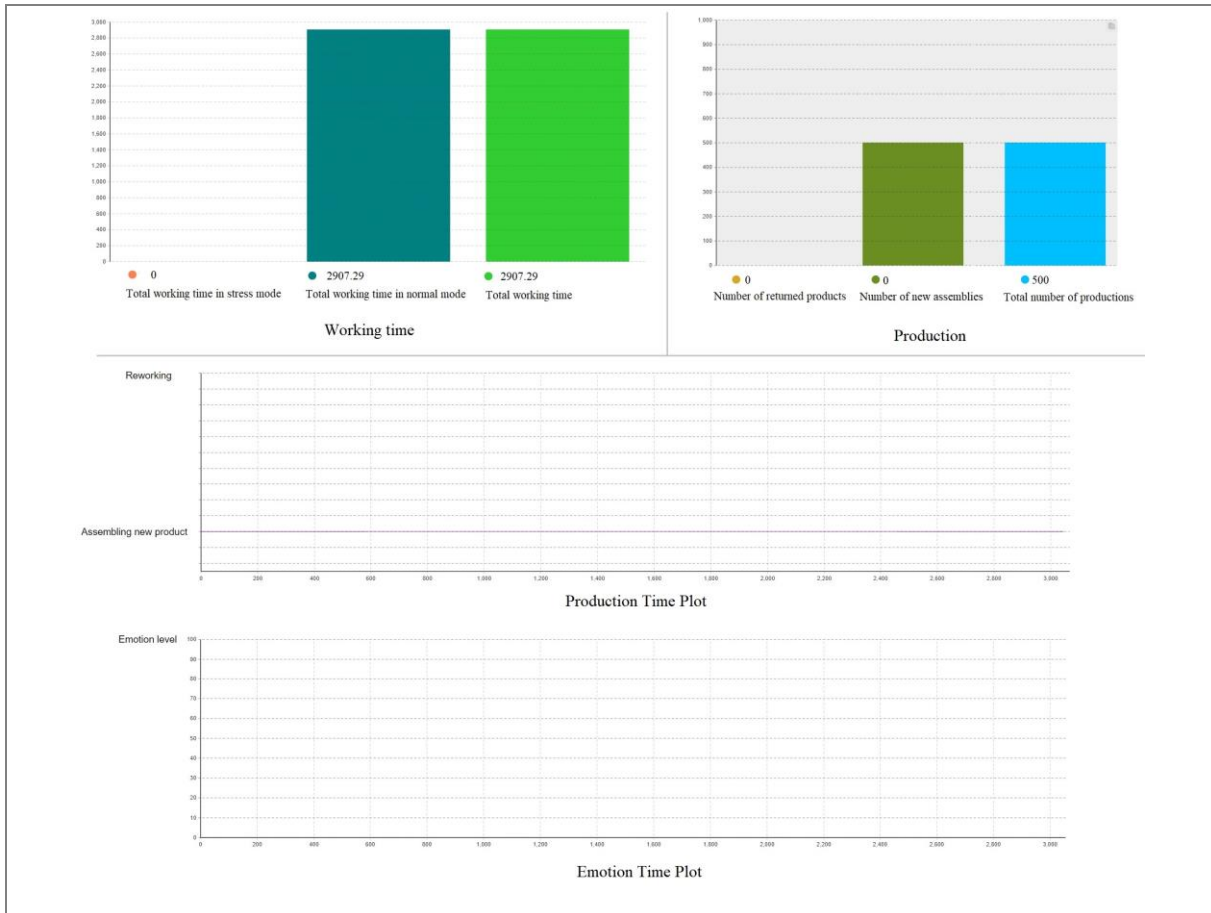


Figure 58 The simulation results of Operator B (Scenario one)

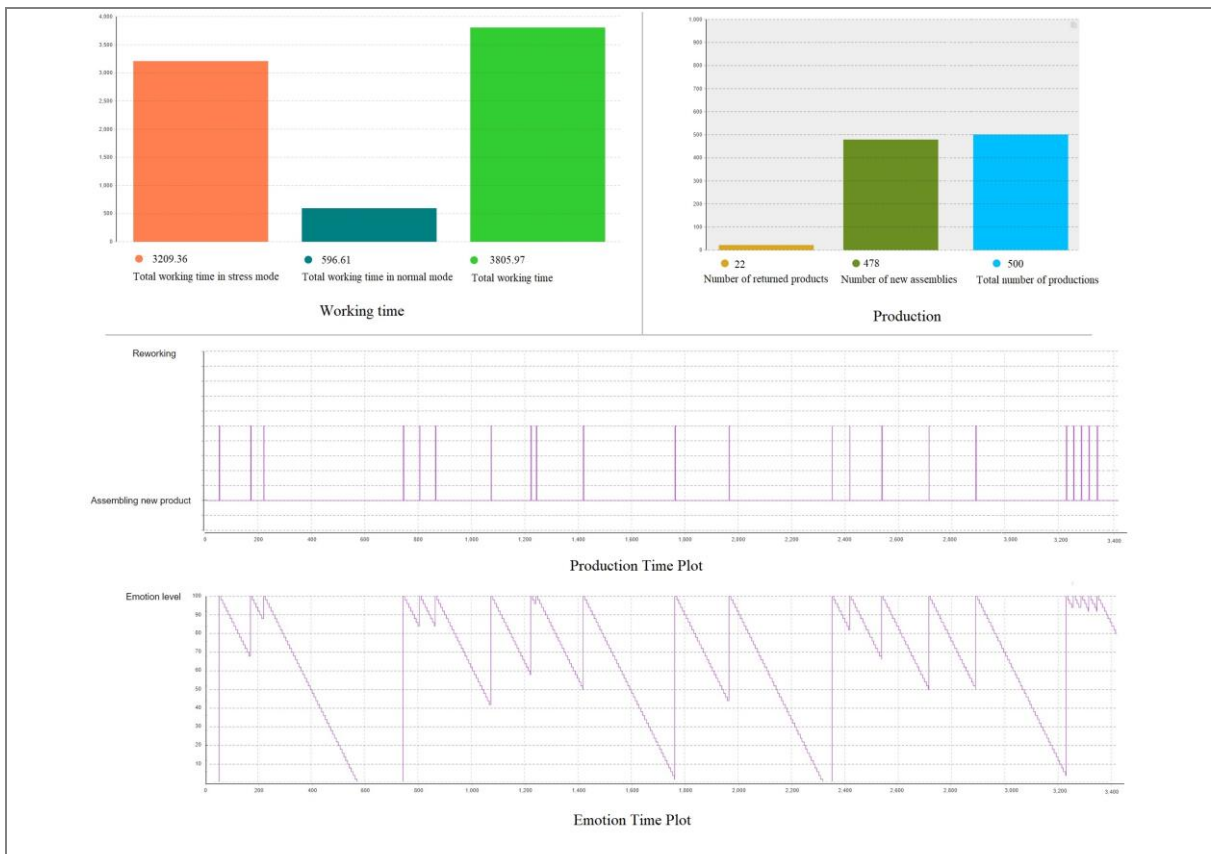


Figure 59 The simulation results of Operator B (Scenario two)



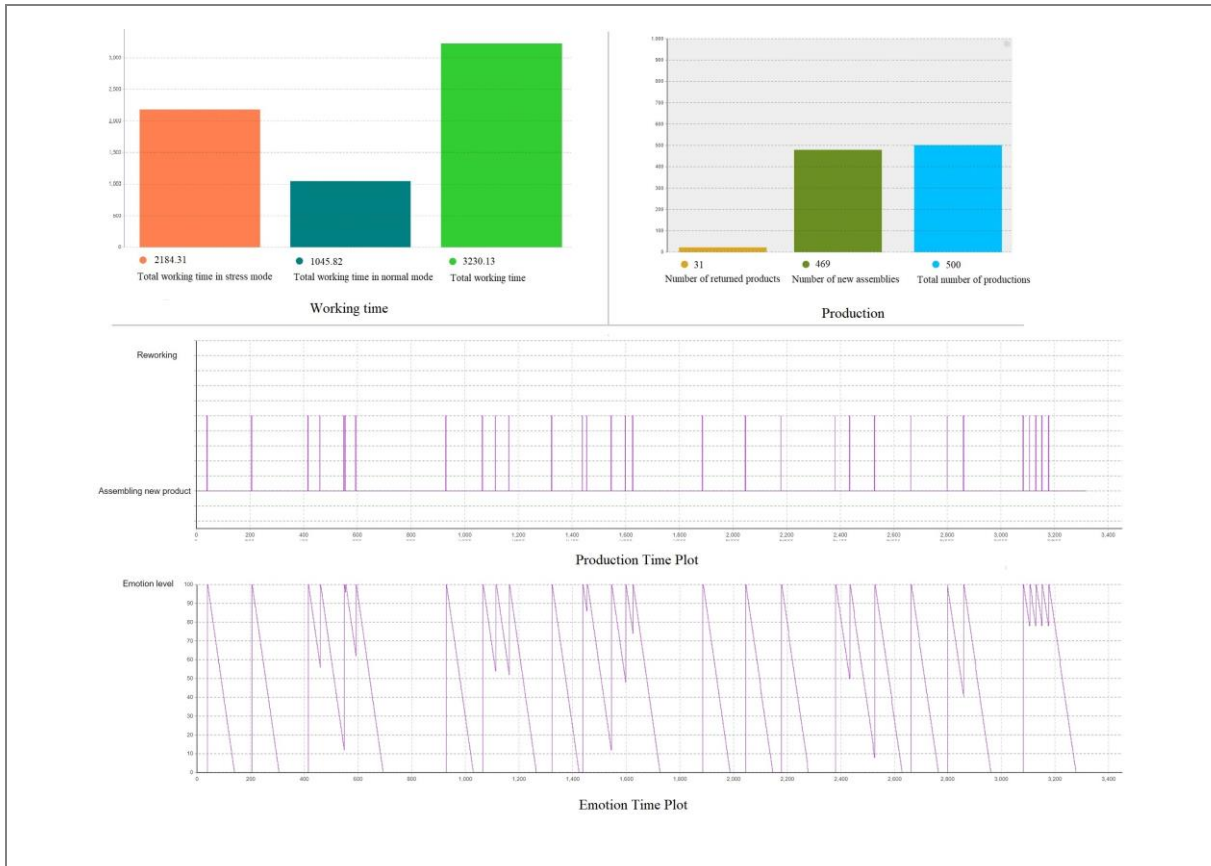


Figure 60 The simulation results of Operator B (Scenario three)

## 4.5 Conclusion

Manufacturing is an active domain for CPHS in which various behavioural patterns may appear. This chapter presented an intelligent manufacturing system whose components manifested emotion-influenced, learning-based, and goal-directed behaviours. Therefore, it provided good support for the inclusiveness and comprehensiveness of our proposed framework.

In this chapter, we showed how purpose-centric, behaviour-centric and execution-centric models can be developed to contribute to the understanding and modelling of a CPHS and ultimately simulate it to reach the intended M&S objectives.

# Conclusion and perspective

CPHS is in rapid growth in various fields. M&S can be leveraged efficiently to understand, analyse and improve CPHSs. Notwithstanding the increased interest in using M&S for CPHS, some barriers are in the way of modellers. We tried to fill the gaps of M&S for CPHS and pave the way for modellers by finding the appropriate responses to the following research questions.

1. How can the CPHS in its social-technical environment be characterized for modellers?
2. How can a CPHS be modelled for its simulation?
3. Which executable infrastructure can be designed to support such a model?

To answer these questions, we first reviewed the CPHS terminology, applications and related technologies. This extended our knowledge about CPHS and cast a new light on the CPHS context. Then we explored the prior works which tried to propose descriptive and modelling frameworks for CPHS. The findings showed the existing approaches toward understanding and developing M&S of CPHS and highlighted shortcomings of the existing structures. Next, we addressed the theoretical knowledge and technologies that seemed advantageous in this thesis. In line with this, we explored the socio-technical ecosystem of CPHS and investigated the well-known modelling approaches, formalism and simulation technology as fundamental issues in M&S.

Using a multidisciplinary approach, the present thesis made an effort to federate the knowledge of social, computer and engineering technics and theories to bring noteworthy contributions to modellers. In this regard, we proposed a framework including three enchainned layers (i.e., PCL, BCL and ECL) such that each layer has a generic model (GPCM, GBCM or GECM) to reach its particular goal and answer one of the research questions. We provided some new contributions within the generic models. To the best of our knowledge, GPCM was the first model using activity theory fundamentals to explain CPHS. In addition, GBCM was the first M&S structure that explained different behavioural patterns of CPHS's components and used HiLLS formalism to make a CPHS simulation model. We also proposed GECM as the first execution model to parameterize and manage the implementation of the CPHS simulation model.

Since the presented models are general, they have broad applicability and can be used for CPHSs regardless of their application domain. We supported the framework by reporting a

CPPS case study. This work provided convincing evidence to ensure the effectiveness of our framework in modelling and simulating different behaviours of CPHS's components.

We can mention some limitations in this thesis. Firstly, we have focused on individual behaviour as the most common human behaviour in CPHSs and did not deal with the simulation of crowd behaviour. A further study with focus on crowd behaviour in CPHS is therefore suggested. Another limitation is related to human cognitive characteristics and abilities. We did consider human features separately, while their mutual influences should not be ignored in some cases (e.g., the impact of emotion in learning). Since we used our generic models to build all CPHS component simulation models, we did not consider interoperability in the modelling. While, modellers may need to combine other models that are not necessarily developed in the same way as our modelling technics. This can be a source of limitation. This thesis did not engage with the validation of behaviours. However, our study can help engineers and social scientists investigate and validate the behaviours of tech tools and humans through M&S.

Given that M&S are the fundamental part of digital twins, despite the aforementioned limitations of our work, our study has taken the first steps towards the development of digital twins for CPHS. Digital Twin is a new simulation technology coping with the challenges of real systems at different stages. This technology has been recognized as a novel generation of simulation that allows high-fidelity mirroring of real entities in cyberspace for various purposes (Graessler & Pöhler, 2017; Josifovska et al., 2019) Although the Digital Twin was first introduced in 2002, its basic concepts and benefits were understood many years ago. In April 1970, an explosion occurred on the Apollo 13 service module that disrupted the mission. The astronauts got into trouble 300,000 kilometres away from home, where no human intervention was possible. However, NASA had at least 15 ground-based simulators. So, NASA's engineers decided to get information from the spacecraft and modify the simulators to match actual flight damage conditions. In this way, they could test different scenarios and make safe decisions to bring the astronauts to earth. Although those simulators were not Digital Twins in the modern sense, they were one of the first use of the digital twin concept.

In the modern sense, Digital Twins can provide much more advantages. This technology can use real-time information for more efficient decision-making and makes predictions about what the outcomes will be in the future (Rasheed et al., 2020). Moreover, it can be helpful for legitimacy where humans' decisions need to be understandable to others (Rasheed et al., 2020). Three subclasses of the Digital Twin have been discussed by Kritzinger et al. (2018) based on the levels of integration. Digital Model without automatic data flow between physical and cyber

objects, Digital shadow makes automatic data flow from physical to cyber objects, and digital twin provides bilateral automatic data flow between physical and cyber parts.

In brief, Digital Twin tries to turn action and facts into perception (required process) and perception into action (optional process). Accordingly, a continuous stream of data is needed to replicate a real object, process, or service and give a real-time outlook of what it is and what is happening. Over the past decade, thanks to the revolutionary advances in sensing, communication and computing technologies, we have been able to acquire more data and perform faster analysis which paved the way for developing Digital Twins. Although much effort has been undertaken to build Digital Twins in recent years, most are aimed at physical systems rather than socio-technical systems. In the past few years, there has been an increasing interest in Digital Twin as an enabler for the coming socio-technical paradigms such as Industry 5.0 in Europe and Society 5.0 in Japan. The dynamicity and complexity of socio-technical systems necessitate using data-driven and model-driven approaches to build Digital Twin. The model-driven approach illustrates the system's behaviour by a set of models, while the data-driven approach helps discover, update, validate and train up the models.

The first challenge which arises in the development of Digital Twins for socio-technical systems is related to the modelling of social behaviours. Human modelling is an area that raises significant differences between the modelling of Cyber-Physical and Cyber-Physical Social Systems. The basic idea of the digital human model is to provide high behavioural fidelity to the extent to which it satisfies the requirements. Behavioural fidelity indicates how well human behaviour that occurs in simulation is consistent with human behaviour in the real system (Folds, 2015). Reaching appropriate behavioural fidelity requires complex M&S techniques. M&S of human behaviour can become even more challenging when there is a need to model a group of people, a so-called simulation of crowd behaviour (Luo et al., 2009; Sycara & Lewis, 2008).

The second challenge is associated with the compatibility of models. Socio-technical systems face heterogeneity of models. From the standpoint of model implementation, models should be made so that other models can work with them. This calls for a model-driven interoperability approach to make a coherent and harmonious network of models.

Since, M&S shapes the core part of Digital Twin, our contributions to the modelling and simulation of CPHS lay a good foundation for studying Digital Twins of socio-technical systems. However, some technical issues such as real-time synchronisation and simulation of crowd behaviour are in need of further investigation.



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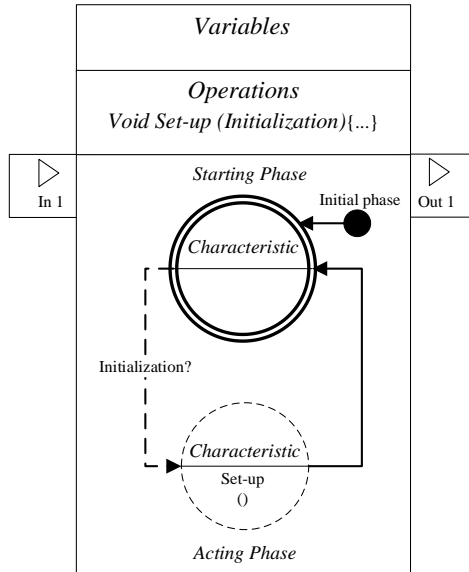
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# Appendix

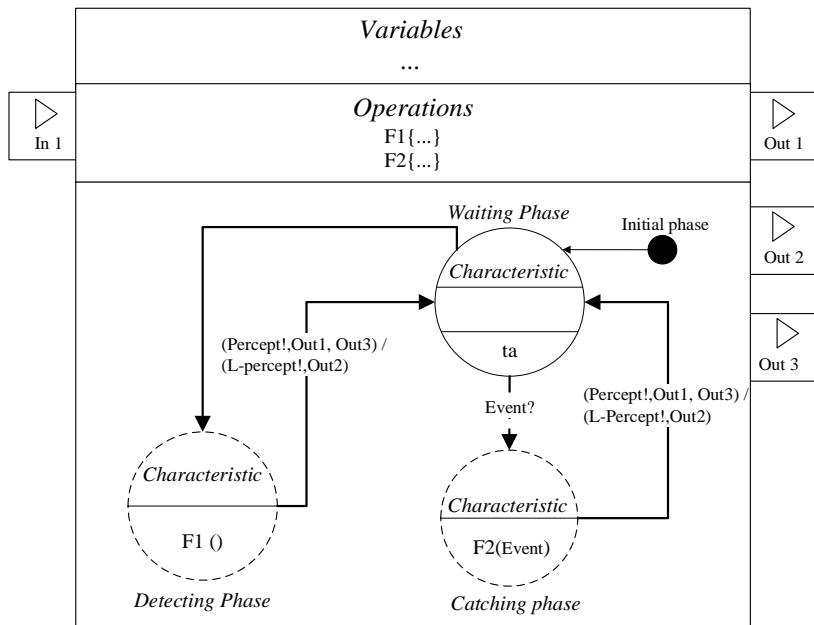
## Appendix A

High-resolution model of H-Systems for CBA HiLLS modelling.

### Active component (Parameters )

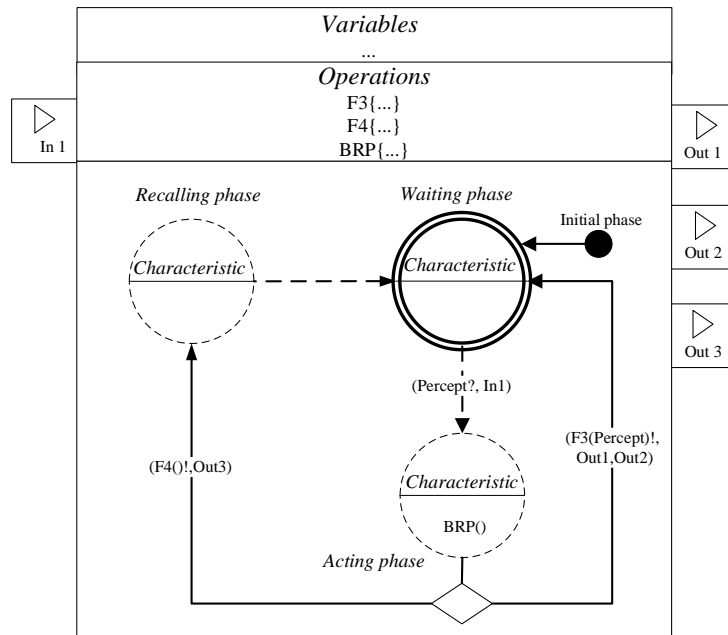


### Communication (Parameters)

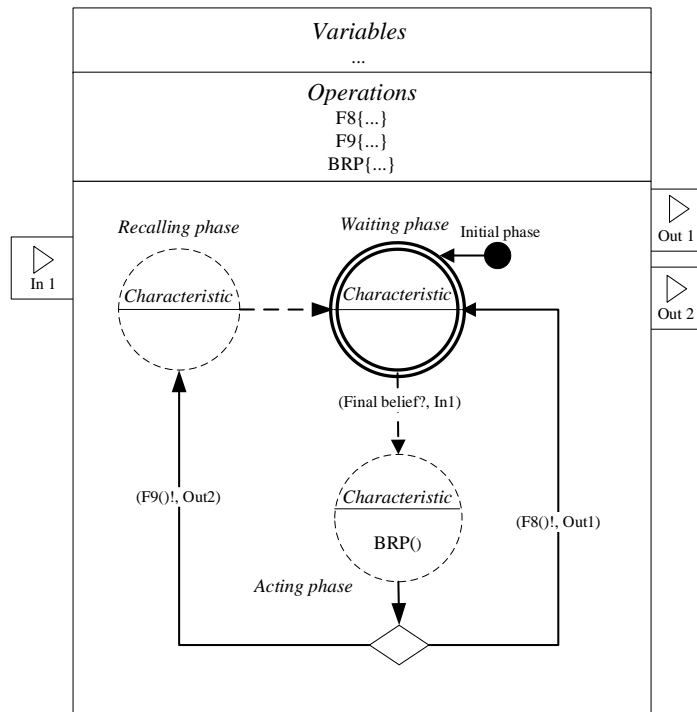




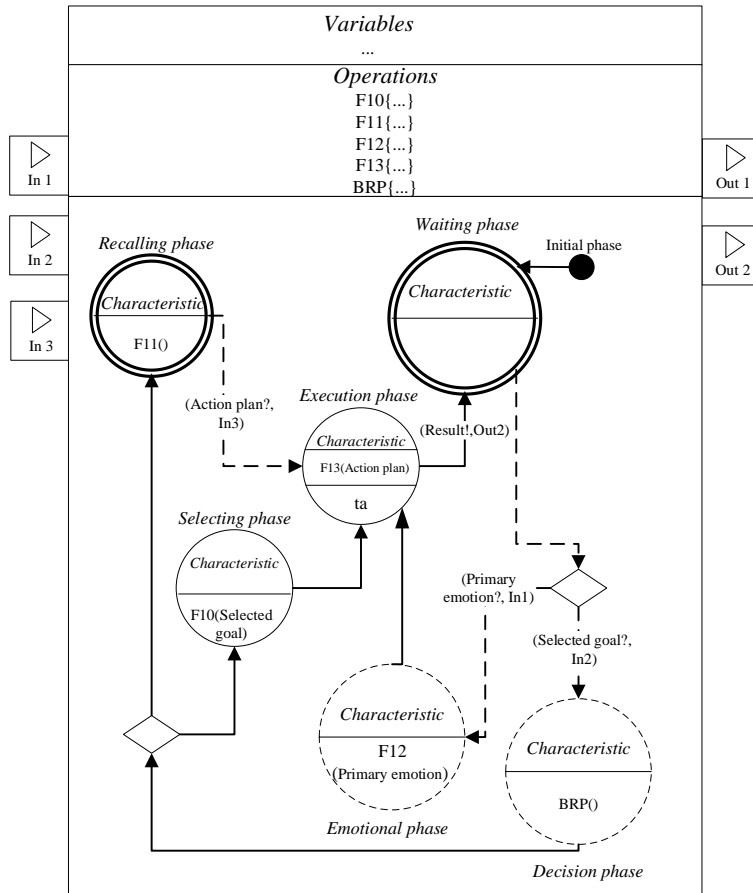
# Belief (Parameters)



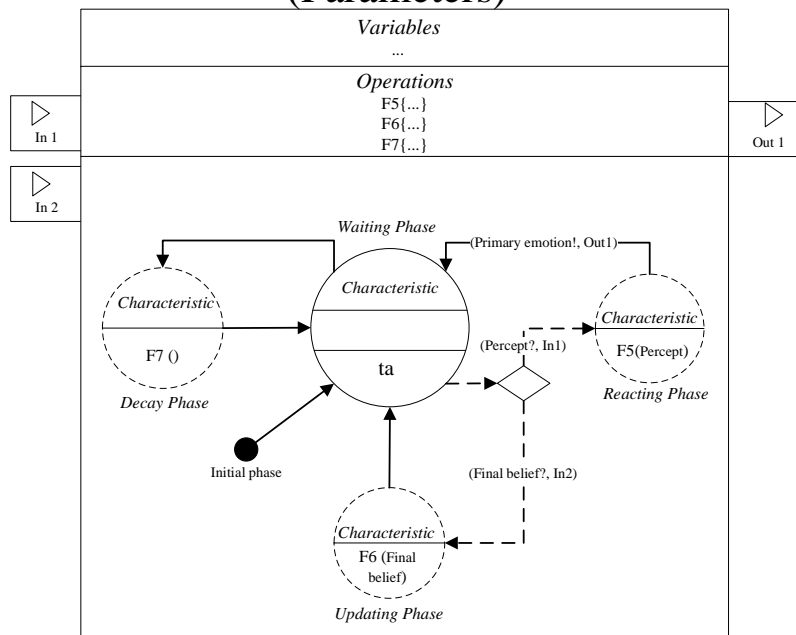
# Desire (Parameters)



# Intention (Parameters)



# Emotion (Parameters)



# Learning (Parameters)

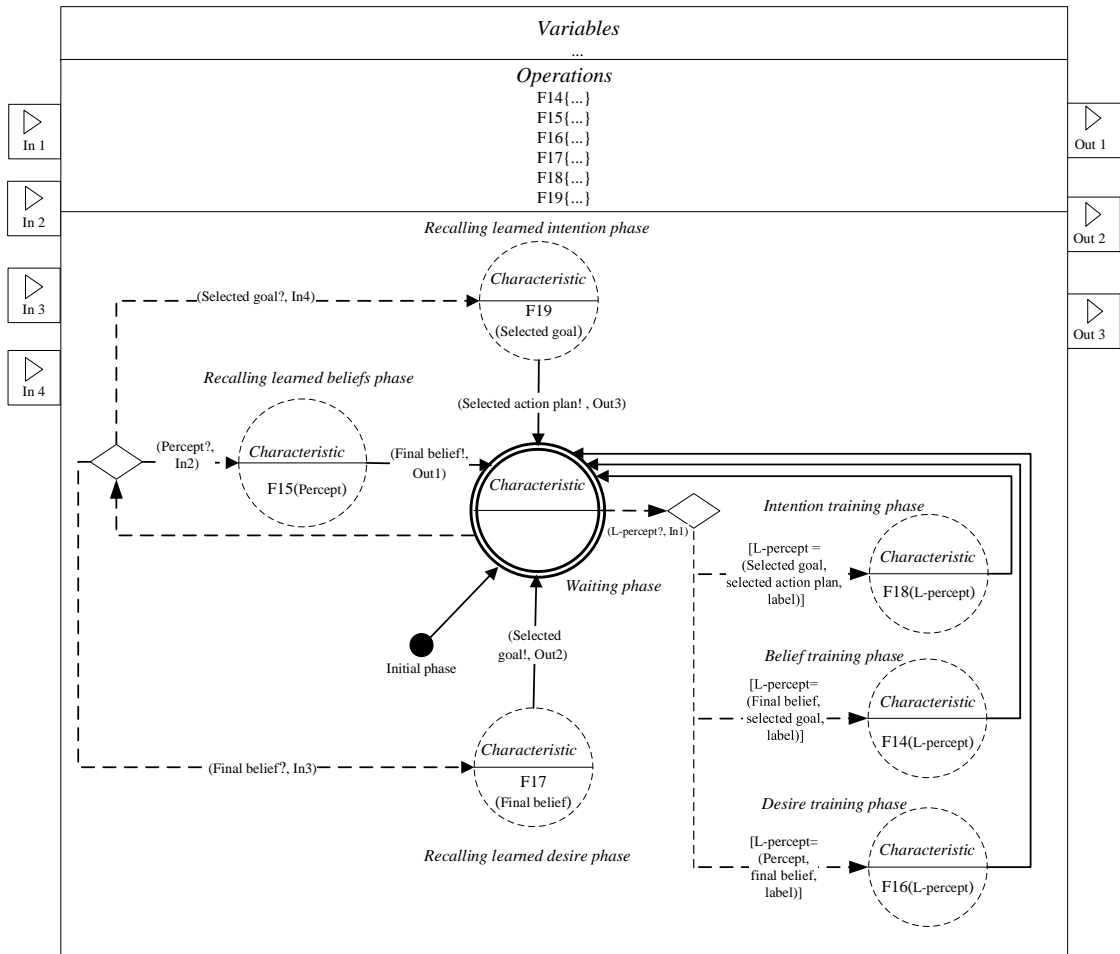


Figure 61 High-resolution model of H-Systems and its behavioural constituents

# Appendix B

Anylogic models of the supervisor and the monitor. The dark phase indicates that the phase is not applicable for this case.

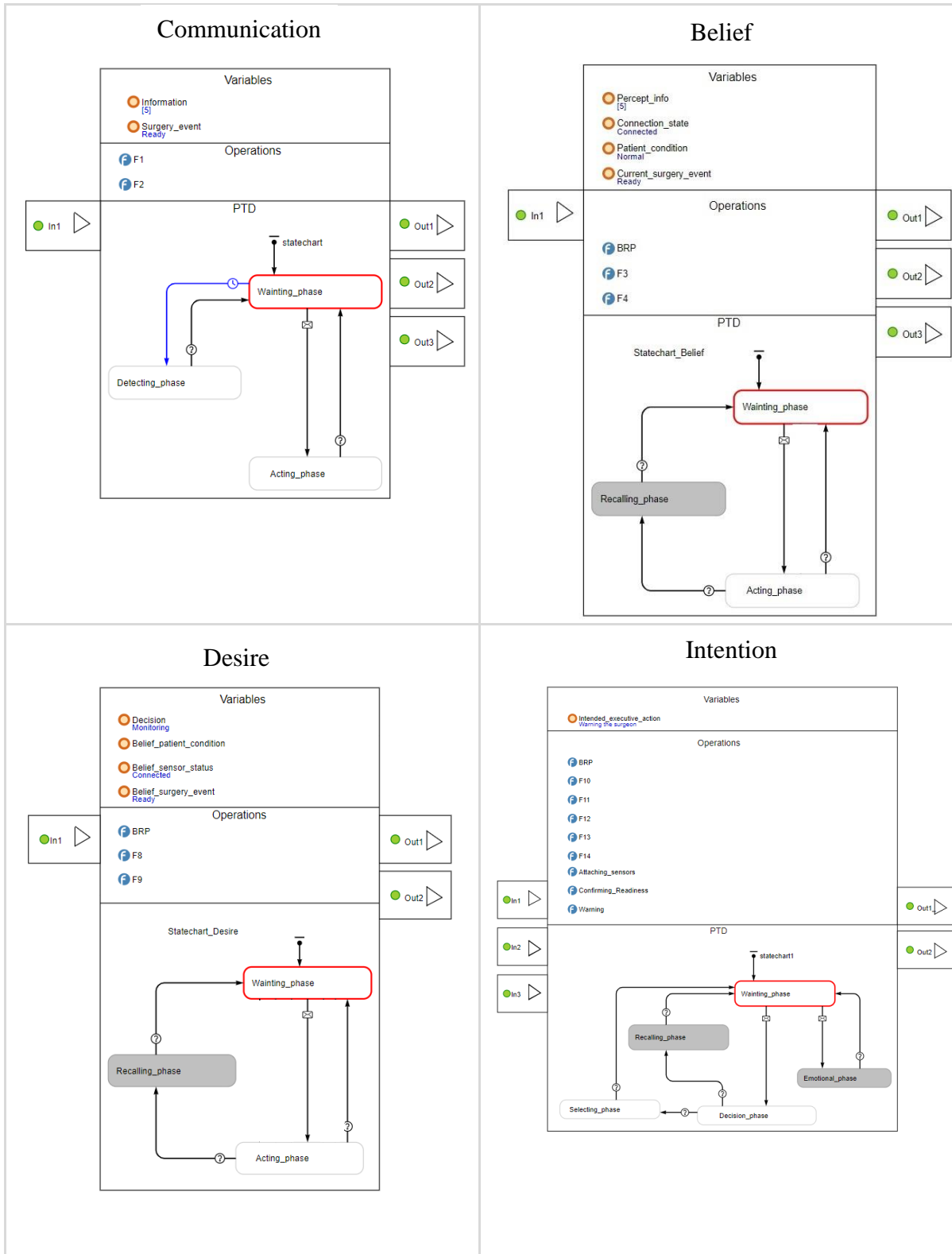



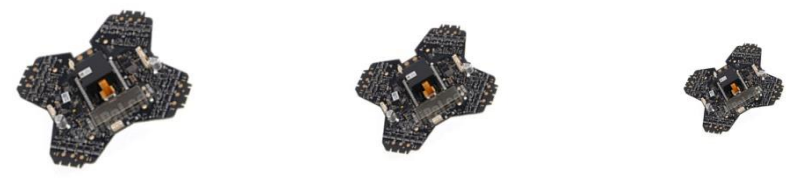

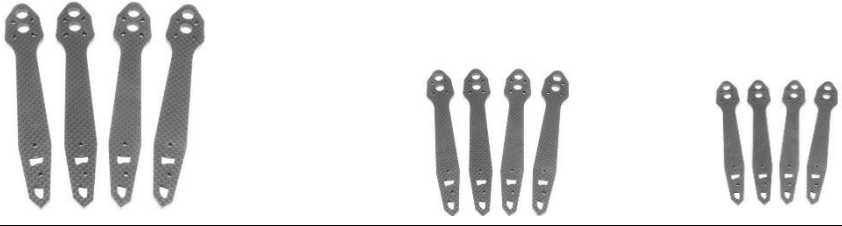



Figure 62 Anylogic simulation models of the supervisor

# Appendix C

Required parts for photography drone manufacturing related to the case study.

Drone parts		
Raw Frame	Small Medium Large	
FRID tag	-	
Battery	1500mAh 5000mAh 10000mAh	
Circuit board	Small Medium Large	
Motors	1800Kv 2300 Kv 7500 Kv	
Arms	Small Medium Large	
Camera	Model A Model B	





Shell	Small Medium Large	
Base	Small Medium Large	
Propeller	Small Medium Large	
Final Product		

Figure 63 Necessary parts to produce a photography drone

# Appendix D

Required diagrams related to the purpose-centric model of the case study.

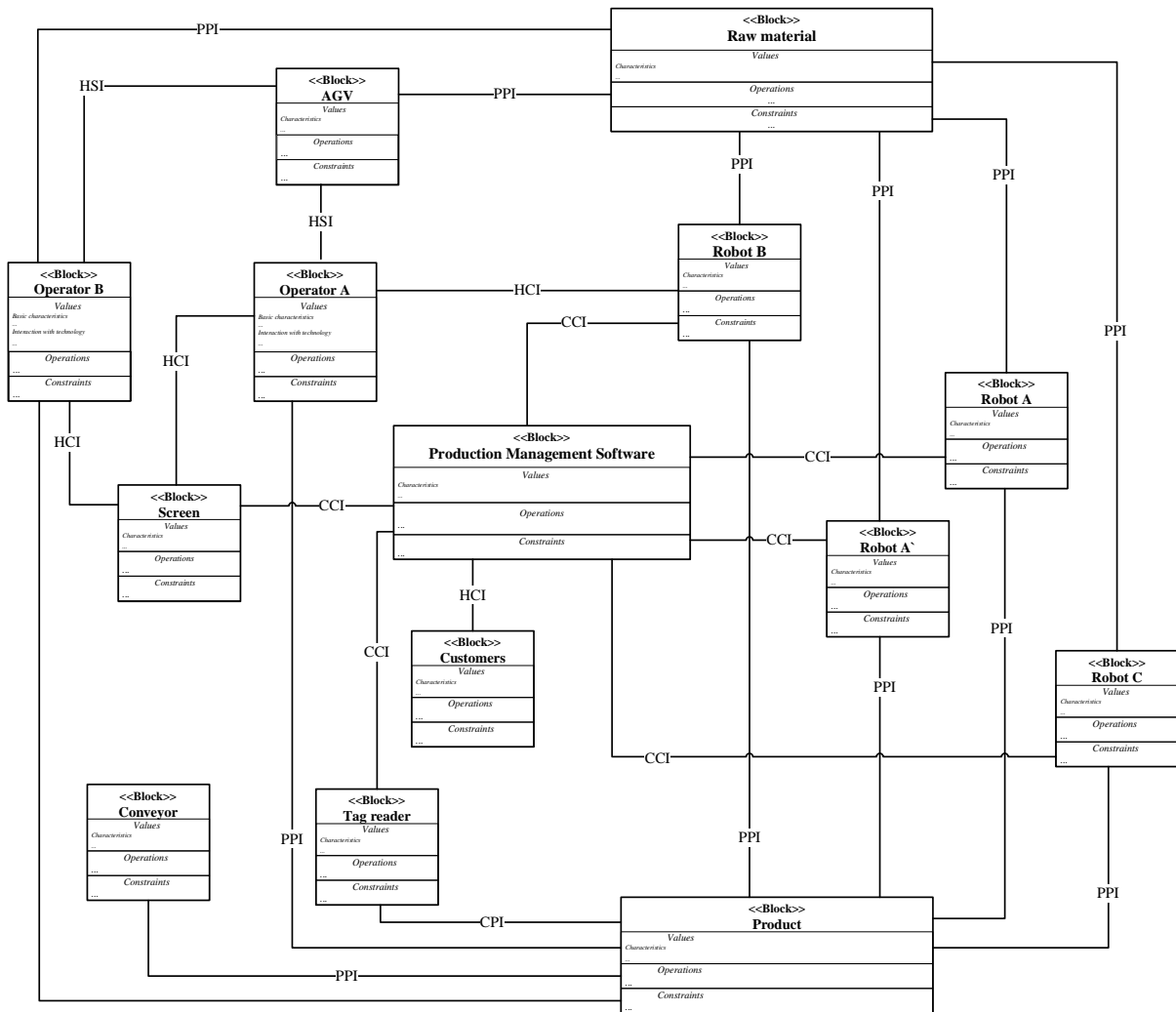


Figure 64 Overview of block diagrams for the case study



To maintain legibility and simplify the connections in the BPMN diagram for readers, the sequence flow between the operations of different actions has been eliminated in the following figure. Thus, the actions are depicted as pools and the removed sequence flows are replaced by the message flows.

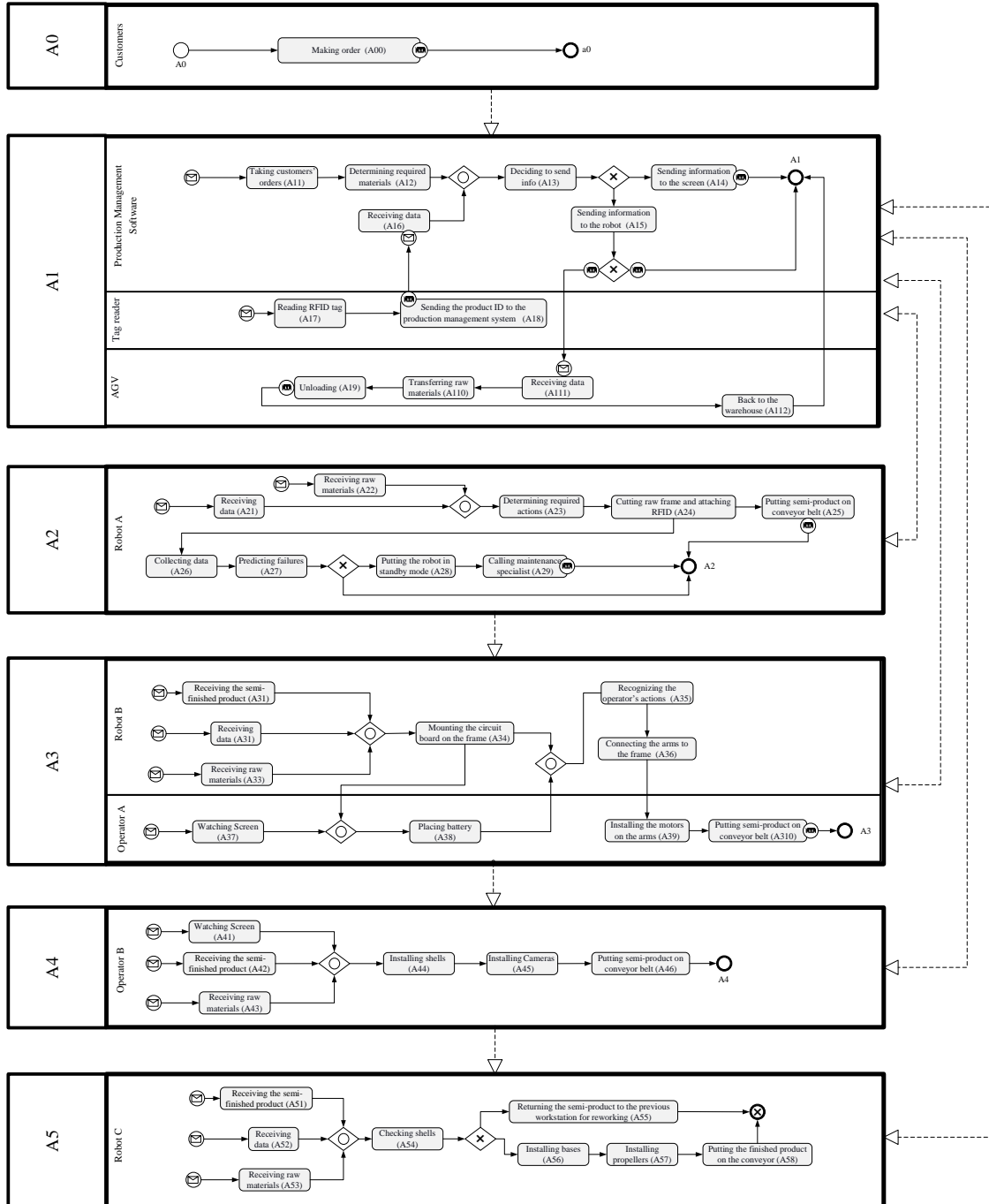
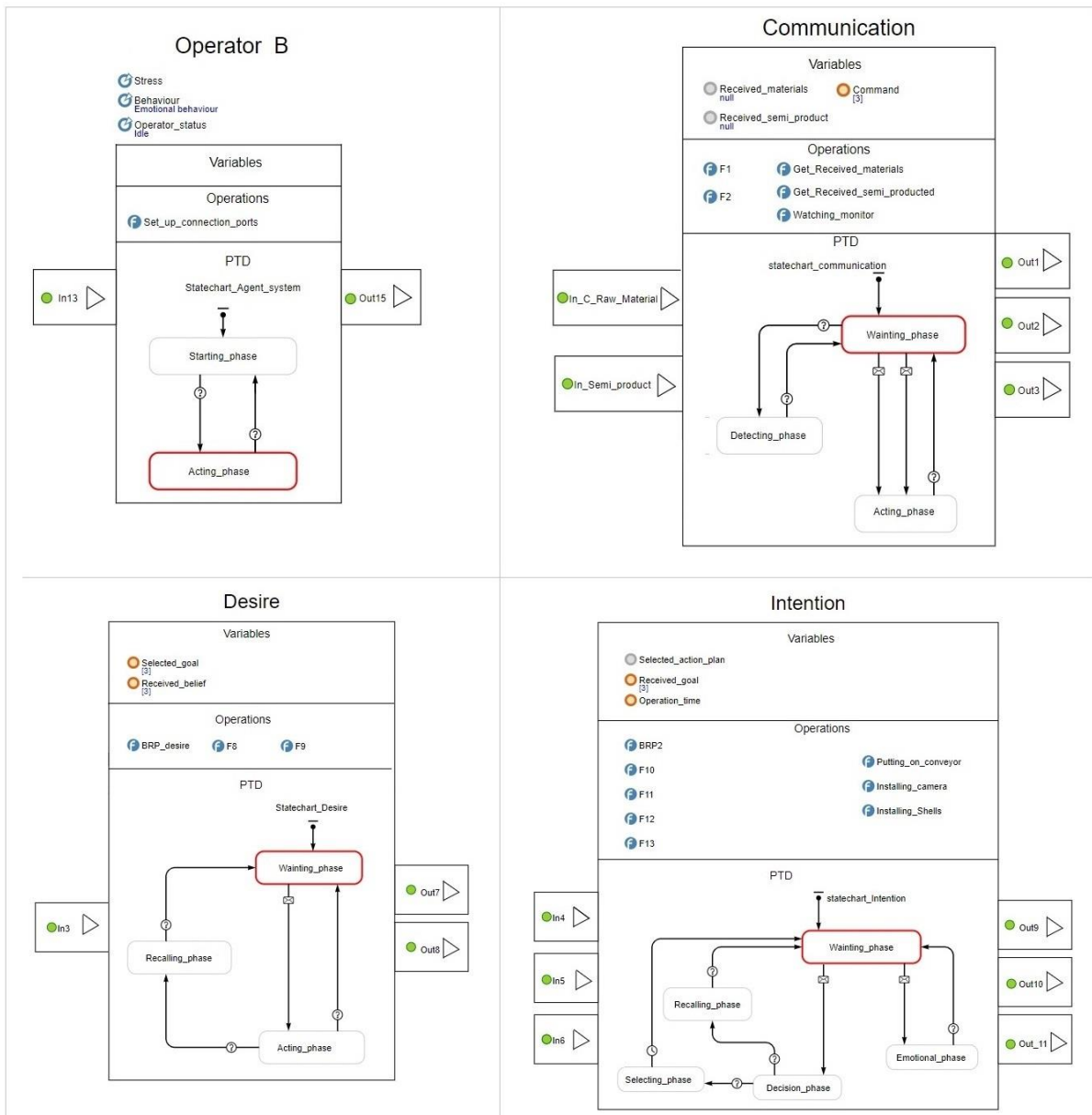


Figure 65 BPMN diagram for the case study

# Appendix E

Anylogic simulation model of operator B in the case study.

This simulation model includes the Central H-System (Operator B) and its behavioural constituents regarding emotional-influenced behavioural pattern. As the stress of operator is considered as a secondary emotion, the emotion flows from the Belief agent to the Emotion agent and from the Emotion agent to the Intention agent.



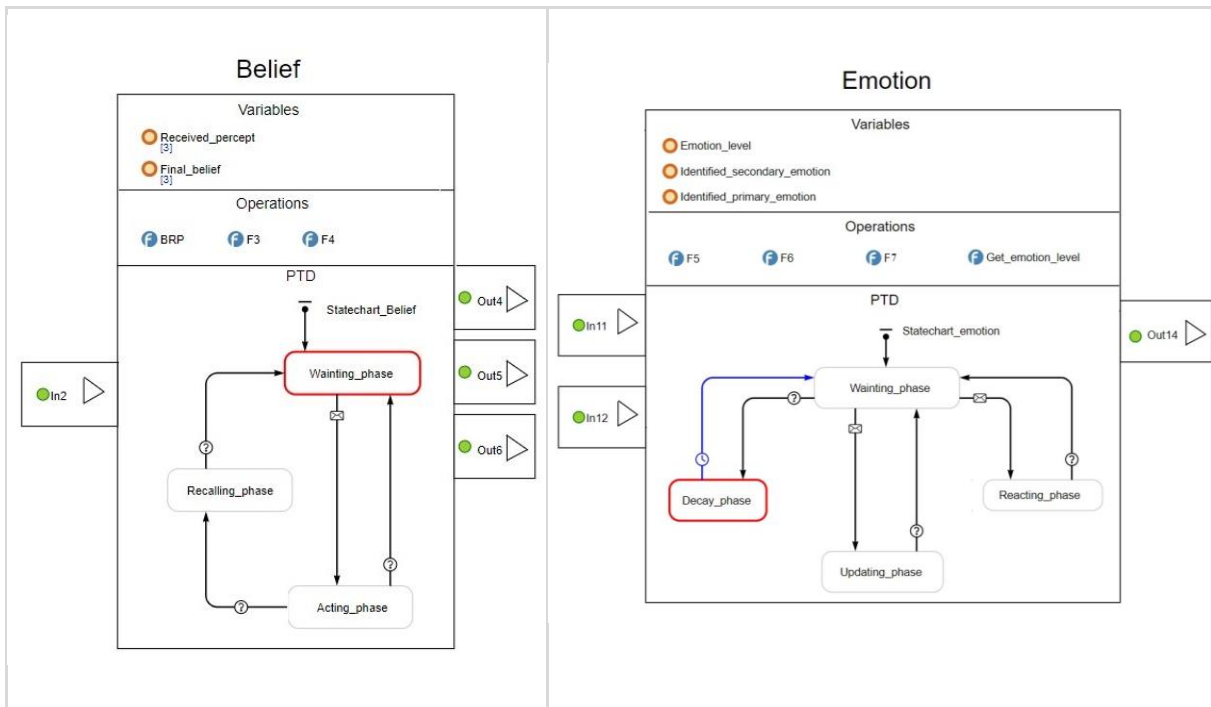


Figure 66 Anylogic simulation models of the operator B in the case study