Toward an anthropocentric approach for intelligent manufacturing systems' control architectures

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Vers une approche anthropocentrée des architectures de contrôle pour les systèmes intelligents de production

THÈSE

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Abstract

Toward an anthropocentric approach for intelligent manufacturing systems' control architectures

Last decades have seen the growth in size and complexity of industrial systems and flows (both physical and informational). Hyper competitive markets, demand atomization and customer requirements level increase, have brought about the need to combine the robustness and performance of centralized systems with the responsiveness of decentralized systems. For the 20 last years, the relevance of these Hybrid Control Architectures has been demonstrated through numerous works. However, they are today hardly present in the industrial landscape. This situation could find some of its roots in a certain lack of genericity and/or Human-System acceptability.

In this research work, the explored path consists in proposing a reference formal framework for the design, modelling, simulation, visualization and evaluation of complex systems' constitutive components and interactions/relations. The purpose of this framework is to bridge the genericity gap identified for Holonic and Hybrid Control Architectures Design regarding complex Multi-Agent Systems (MAS), but also to promote human inclusion into these. To this end and to promote the socio-technical representation of systems, the proposed relationships model is grounded on the nature human societies' ones.

Keywords: *Holonic Control Architectures*, *Hybrid Control Architectures*, *Human-Centred approaches*, *Socio-Technical Systems*, *Industry 4.0*, *Industry 5.0.*

Résumé

Vers une approche anthropocentrée des architectures de contrôle pour les systèmes intelligents de production

Les dernières décennies ont vu croître en taille et en complexité les systèmes industriels ainsi que leurs flux (matériels et informationnels). L'hyper compétitivité des marchés, l'atomisation de la demande et l'augmentation des niveaux d'exigences clients ont fait émerger le besoin de coupler la robustesse et la performance des systèmes centralisés à la réactivité des systèmes décentralisés. Au cours des 20 dernières années, la pertinence de ces Architectures de Contrôle Hybrides a pu être démontrée à travers de nombreux travaux. Toutefois, leur déploiement reste aujourd'hui limité. Cette situation semble pouvoir être rapporté à un manque de généricité ou d'acceptabilité Humain/Système.

La piste explorée dans ce travail de recherche consiste à proposer un cadre formel de référence pour la conception, modélisation, simulation, visualisation et évaluation des composants et des interactions/relations constitutifs des systèmes complexes. L'objectif de ce cadre est d'apporter la généricité manquant aujourd'hui pour le design des architectures de contrôle holoniques et hybrides pour les systèmes multi-agents complexes, mais également de favoriser l'inclusion de l'humain dans ces derniers. Pour ce faire, la nature des relations proposées s'appuie sur celles observables au sein des sociétés humaines, afin de favoriser la représentation des systèmes comme socio-techniques.

Mots-clés: *Architectures de contrôle holoniques*, *Architectures de contrôle hybrides*, *Approches centrées-humain*, *Systèmes Socio-techniques*, *Industrie 4.0*, *Industrie 5.0.*

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Notations and acronyms

Notations related to the relationships

$\mathcal{R}^{Direct}_{i \rightleftarrows j}$	Direct relationship between holons i and j
$\mathcal{R}^{Direct}_{i \longrightarrow j}$	Direct relationship of holon i with j
$\mathcal{R}^{PR}_{i \xrightarrow[PARENT]{} j}$	Notation for holon i parent of holon j
$\mathcal{R}^{PR}_{j \xrightarrow[CHILD]{} i}$	Notation for holon j child of holon i
$\mathcal{R}^{OR}_{i \xrightarrow[OWNER]{} j}$	Notation for holon i owner of holon j
$\mathcal{R}^{OR}_{j \xrightarrow[OWNED]{} i}$	Notation for holon j owned by holon i
$\mathcal{R}^{DR}_{i \xrightarrow[REQUIRED]{} j}$	Notation for holon i required by holon j
$\mathcal{R}^{DR}_{j \xrightarrow[DEPENDENT]{} i}$	Notation for holon j dependent on holon i
$\mathcal{R}^{HR}_{i \xrightarrow[SUPERIOR]{} j}$	Notation for holon i superior of holon j
$\mathcal{R}^{HR}_{j \xrightarrow[SUBORDINATED]{} i}$	Notation for holon j subordinated to holon i
$\mathcal{R}^{SCR}_{i \leftrightarrows j}$	Emergent or Social Contact relationship between holons i and j
$\mathcal{R}^{SCR}_{i \Longleftrightarrow j}$	Symmetric relationship between holons i and j
$\mathcal{R}^{SCR}_{i \Longrightarrow j}$	Transitive relationship from holon i to holon j
$\mathcal{R}^{C-PR}_{i \Longleftrightarrow j}$ or $\mathcal{R}^{C-PR}_{j \Longleftrightarrow i}$	Co-Parental Relationship between holons i and j
$\mathcal{R}^{C-OR}_{i \Longleftrightarrow j}$ or $\mathcal{R}^{C-OR}_{j \Longleftrightarrow i}$	Co-Ownership Relationship between holons i and j
$\mathcal{R}^{C-DR}_{i \Longleftrightarrow j}$ or $\mathcal{R}^{C-DR}_{j \Longleftrightarrow i}$	Co-Dependency Relationship between holons i and j
$\mathcal{R}^{C-HR}_{i \Longleftrightarrow j}$ or $\mathcal{R}^{C-HR}_{j \Longleftrightarrow i}$	Co-Hierarchical Relationship between holons i and j
$\mathcal{D}^{PR}_{i \xrightarrow[PARENT]{} j}$	Parenthood degree of holon i over holon j

$\mathcal{D}^{PR}_{j \xrightarrow[CHILD]{} i}$	Childhood degree of holon j to holon i
$\mathcal{D}^{OR}_{i \xrightarrow[OWNER]{} j}$	Ownership degree of holon i over holon i
$\mathcal{D}^{OR}_{j \xrightarrow[OWNED]{} i}$	Degree holon j is owned by holon i
$\mathcal{D}^{DR}_{i \xrightarrow[REQUIRED]{} j}$	Degree holon i is required by holon j
$\mathcal{D}^{DR}_{j \xrightarrow[DEPENDENT]{} i}$	Dependency degree of holon j to holon i
$\mathcal{D}^{HR}_{i \xrightarrow[SUPERIOR]{} j}$	Superiority degree of holon i over holon j
$\mathcal{D}^{HR}_{j \xrightarrow[SUBORDINATED]{} i}$	Subordination degree of holon j to holon i
$\mathcal{D}^{C-PR}_{ij,k}$	Relative C-PR degree between holons i and j regarding holon k
$\mathcal{D}^{C-PR}_{ij}$	Absolute C-PR degree between holons i and j
$\mathcal{D}^{C-OR}_{ij,k}$	Relative C-OR degree between holons i and j regarding holon k
$\mathcal{D}^{C-OR}_{ij}$	Absolute C-OR degree between holons i and j
$\mathcal{D}^{C-DR}_{ij,k}$	Relative C-DR degree between holons i and j regarding holon k
$\mathcal{D}^{C-DR}_{ij}$	Absolute C-DR degree between holons i and j
$\mathcal{D}^{C-HR}_{ij,k}$	Relative C-HR degree between holons i and j regarding holon k
$\mathcal{D}^{C-HR}_{ij}$	Absolute C-HR degree between holons i and j

Notations related to the formal model

$\mathbb{R}_+$	Positive reals
$Card(\{x\})$	Cardinal of the {x} set
$t \in [0; T]$	Time variable
$T \in \mathbb{R}_+$	Upper time variable limit
$\mathcal{E}$	General ecosystem
$\mathcal{E}_i$	Holon i's ecosystem
$\mathcal{H}$	Holons of the Ecosystem $\mathcal{E}$
$\mathcal{H}_i$	Holon i
$\mathcal{R}$	Relationships of the Ecosystem $\mathcal{E}$

$\mathcal{R}_i$	Holon i's Relationships
Φ_i	Holon i's cognitive/Decision-making function
$\mathcal{T}_i$	Holon i's transformation function
$\mathcal{M}_i$	Holon i's measurement function
$\mathcal{C}_i$	Holon i's capabilities
$\mathcal{O}_i$	Holon i's objectives
$\mathcal{U}_i$	Holon i's abilities, skills
$\mathcal{Y}_i$	Holon i's perception
$\mathcal{D}_i$	Holon i's Data
P_i	Holon i's processes
$\{a_k\}, k \in \mathbb{R}_+$	Actions constitutive of a process $\rho_i \in \mathrm{P}_i$

Notations related to the MAS implementation

${A^{\mathrm{Resource}}}_i$	Resource agent i
${A^{\mathrm{Product}}}_i$	Product agent i
$\mathcal{X}_i$	Agent i's configuration
X_i	Agent i's physical state
AMS	Agent Management System
DF	Directory Facilitator
EMU	Emulator of the operating system
$SnifferAgent$	Sniffer agent to collect inter-agents messages
$ProductLauncher$	Product agents creator
RMA	Remote Management Agent
$Database$	Database entry manager
$plcA$	PLC agent for Zone A actuators
$plcB$	PLC agent for Zone B actuators

$plcD$	PLC agent for Zone D actuators
$rfidA$	RFID agent for Zone A
$rfidB$	RFID agent for Zone B
$rfidD$	RFID agent for Zone D
$Platform$	Platform agent
$Mq1, Mq2$	Machining stations 1 & 2
$M1, M2$	respectively Plate and Chip agents assembly stations
ASn, $n = 0..3$	Zone A's shifts
$BS0, BS1$	Zone B's shifts
$DS1$	Zone D's shift
p	Product's position on the platform
$s_{Resource}$	Transfer to next position/resource
τ_n, $n = 1..2$	Nature & location of machining operation
α_n, $n = 1..4$	Nature & location of assembly operation
$d_{Resource}$	Draw a Dot
$l_{Resource}$	Draw a Line
μ_n, $n = 1..4$	Plate assembly
ν_n, $n = 1..4$	Chip assembly
MO_n	Manufacturing Orders
$N_i(t)$	Agent i's Neighbors (at time t)

Acronyms

Generic acronyms

AGV	Automated Guided Vehicles
AI	Artificial Intelligence
AID	Agent IDentifier

AMS	Agent Management System
AP	Agent Platform
APS	Advanced Planning and Scheduling
APU	Autonomous Production Unit
AR	Augmented Reality
BPM	Business Process Management
CIM	Computer Integrated Manufacturing
COBALT	COmmon Base for Agent deveLopmenT
CPS	Cyber-Physical System
DAI	Distributed Artificial Intelligence
DCS	Distributed Control System
DF	Directory Facilitator
DT	Digital Twin
ERP	Enterprise Resource Planning
FiFo	First-in / First-out
GEMS	Generic Error Modelling System
GST	General System Theory
HCA	Holonic Control Architecture
HCD	Human-Centred Design
HCI	Human-Computer Interaction
HitL	Human-in-the-Loop
HMI	Human-Machine Interface
HMS	Holonic Manufacturing System
HSI	Human-System Integration
ICT	Information and Communication Technologies

IHA	Interface Holon Architecture
IoT	Internet of Things
IMS	Intelligent Manufacturing System
JADE	Java Agent DEvelopement framework
JIT	Just-in-Time
MAS	Multi-Agent System
MES	Manufacturing Execution System
MO	Manufacturing Order
MR	Mixed Reality
P2P	Peer-to-Peer
PAC	Production Activity Control
PDS	Product Driven System
QRQC	Quick Response Quality Control
R2W	Ready To Work
RFID	Radio-Frequency IDentification
SCM	Supply Chain Management
SLR	Systematic Literature Review
SMCS	Smart Manufacturing Control System
SNS	Social Network Services
S&OP	Sales and Operations Planning
TPS	Toyota Production System
TOPASE	TracilOgis Platform Agent SystEm
UML	Unified Modelling Language
VR	Virtual Reality
VSM	Viable System Model

WHA	Worker Holon Architecture
WWW	World Wide Web

Control Architectures

ADACOR	ADAptive holonic COntrol aRchitecture
ARTI	Activity Resource Type Instance
D-MAS	Delegate Multi-Agent System
EMH	Event Management Holonic architecture
EPC Global Network	Electronic Product Code Global Network
HCBA	Holonic Component-Based Architecture
H^2CM	Holonic Hybrid Control Model
ONTO-PDM	ONTOlogy for Product Data Management
ORCA	dynamic Optimized & Reactive Control Architecture
PRONTO	PRoduct ONTOlogy
PROSA	Product-Resource-Order-Staff Architecture
PROSIS	Product-Resource-Order-Simulation for Isoarchy Structure
RAMI 4.0	Reference Architecture Model for Industry 4.0
REDCA	REcursive hybriD Control Architecture
SoHMS	Service-oriented Holonic Manufacturing System
SOM	Semantic Object Model
SURFER	SURveillance active Ferroviaire

IoT and CPS derivatives

ACPS	Anthropocentric Cyber-Physical System
CIoT	(1) Consumer-Internet of Things ou (2) Cognitive Internet of Things
CPHS	Cyber-Physical Human(-e) System
CPIS	Cyber-Physical Intergrated Society

CPPS	Cyber-Physical Production System
CPSE	Cyber-Physical Socio-Ecosystem
CPSS	Cyber-Physical Social System
HCPS	Human(-e)(-ized) Cyber-Physical System
HIoT	Humanized Internet of Things
Hitl CPS	Human-in-the-Loop Cyber-Physical System
I-CPHS	Industrial Cyber-Physical Human(-e) System
II	Industrial Internet
IIoT	Industrial Internet of Things
IoE	Internet of Everything
IoNT	Internet of Nano Things
IoP	Internet of People
IoS	Internet of Services
SCPS	Socio-Cyber-Physical System
S-Hitl CPS	Social Human-in-the-Loop Cyber-Physical System
SIoIA	Social Internet of Industrial Assets
SIoIT	Social Internet of Industrial Things
SIoT	Social Internet of Things
SWoT	Social Web of Things

Relating to the literature formal models

AR	Authority Ranking
CLOR	Co-Location Object Relationship
CS	Communal Sharing
CWOR	Co-Work Object Relationship
EM	Equality Matching

MP	Market Pricing
OOR	Ownership Object Relationship
POR	Parental Object Relationship
SOR	Social Object Relationship

Relating to the proposed formal model

DR	Dependency Relationship
C-DR	Co-Dependency Relationship
HR	Hierarchical Relationship
C-HR	Co-Hierarchical Relationship
OR	Ownership Relationship
C-OR	Co-Ownership Relationship
PR	Parental Relationship
C-PR	Co-Parental Relationship
SCR	Social Contact Relationship

Relating to institutions and organizations

ACM	Association for Computing Machinery
ANRT	Association Nationale de la Recherche et de la Technologie
APICS	American Production and Inventory Control Society
ASCM	Association for Supply Chain Management
BASE	Bielefeld Academic Search Engine
CNRS	Centre National de la Recherche Scientifique
CRAN	Centre de Recherche en Automatique de Nancy
FIPA	Foundation for Intelligent Physical Agents
IEEE	Institute of Electrical and Electronics Engineers

ISO	International Organization for Standardization
ITAS	Institute for Technology Assessment and Systems Analysis
ITU	International Telecommunication Union
KIT	Karlsruhe Institute of Technology
MESA	Manufacturing Enterprise Solutions Association
UL	Université de Lorraine - Lorraine University

Chapter 1

Context and issues

1.1 General Context

This thesis is a continuation of the work of the Interdisciplinary Research Laboratory in Lorraine (CRAN[1]). The Ph.D thesis project was initially carried out in collaboration with a furniture manufacturer (CIFRE contract[2]).

Over the past twenty years, works from the CRAN have shown the need to control/synchronize material and information flows as well as the importance of keeping these flows flexible and adaptable to market demand. The work presented in this dissertation finds its roots in the PDS project initiated in the 2000s, placing the information-carrying product at the heart of the production systems' decision-making process. In this paradigm, the product agent is the pivot ensuring synchronization and consistency between centralized system and distributed decision-making entities. The idea behind PDS was to promote centralyzed/decentralyzed decision-making entities' interoperability, rather than classic centralized systems' integration.

First works have aimed to bring the proof-of-concept of this new paradigm through case-by-case instantiation. During this first period, many different approaches have been taken to implement product-driven control vision, such as model-driven approach for interoperability[17, 193, 66], rebalancing and rescheduling based approaches for production performance [90, 110, 130, 74], or system engineering-based ones [49, 135]. Then, more recent works have focused on centralized/decentralized coupling optimization, for instance based on combined simulation of production and control processes [48], Viable System Model-Based evaluation and optimization [227], or human-inspired negotiation algorithm for consensus [116]. Hence, after concept enunciation, testing, and optimizing, current and future works are bringing PDSs, and more generally hybrid control architectures, one step further with human-centered/inspired and social developments. Figure 1.1 provides an illustration of this chronology.

Gouyon's thesis work falls particularly within this context, and constitutes one of the first

[1]CRAN: `http://www.cran.univ-lorraine.fr/index.php?codelangue=EN`

[2]CIFRE: Convention Industrielle de Formation par la Recherche / Industrial Agreements for Training through Research

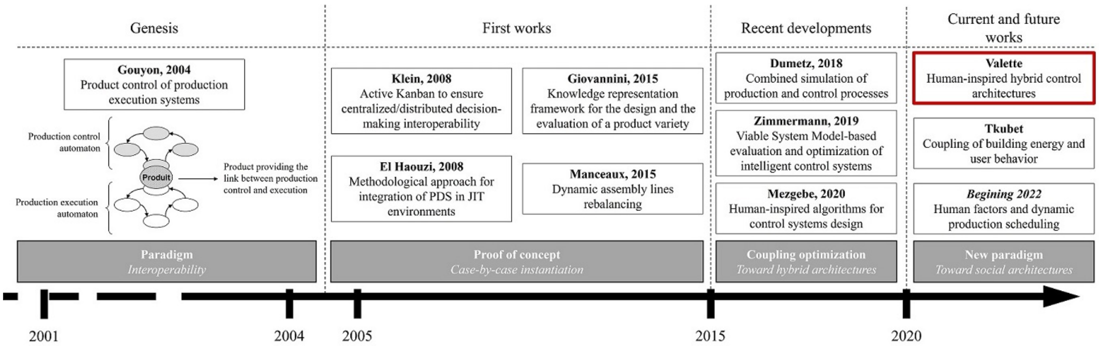


Figure 1.1: Continuity of CRAN's work from the 2000s to today ([29])

contributions [67]. In his definition of a PDS, Gouyon starts from the concept of "product holon" introduced by the PROSA reference architecture [202]. The product, carrying alone the information necessary for the consistency of the physical flows into information relating to its own manufacture, is consequently *de facto* integrated to the production control loop [114]. Then, considering the decentralization of decision-making power to low-level entities, the product is consequently invested with the capacity and responsibility to control its own evolution and to communicate and collaborate with its environment. Under these two conditions, the system is product-driven [67]. This product-oriented approach for system interoperability was equally closely related to the Intelligent Manufacturing Systems (IMS) program [72, 222], and more particularly to its Holonic Manufacturing Systems (HMS) branch. This latter paradigm consisting in the transposition of the concept of "holon"[91] to manufacturing systems, to ease low-volume, high-variety productions.

As part of the IMS program, the HMS paradigm was intended to bring stability to disturbed systems, adaptability and flexibility regarding production changes, and efficiency regarding resources consumption. From PROSA in 1998 to ARTI [194, 195] in 2019, the holonic manufacturing paradigm has continuously evolved to answer these issues. Its developments have brought concrete and encouraging results, notably thanks to successful implementations of Holonic Control Architectures (HCA) in industrial environments [85, 99, 148, 96, 134, 62, 84]. Historically, the implementation of control architectures for complex-adaptable systems has mainly stayed based on the paradigms of Distributed Artificial Intelligence (DAI) and object-oriented programming. We can notably cite the following intelligent agents-based systems' architectures: YAMS [140], InteRRaP [122], AARIA [141], METAMORPH [112], HCBA [85], FrMS [158], ADACOR [99], Pabadis'Promise [143], D-MAS [204], PROSIS [148], or NEIMS [182]. This search for an effective implementation of HMS remains a highly attractive subject within the research community working on agile-adaptable systems, as shown by recent developments ORCA-FMS [134], ADACOR2 [18] and SoHMS [62]. However, despite their results, attractiveness and manufacturers' strong needs, notably motivated by the march toward Industry 4.0, HCAs' deployment within manufacturing systems is still limited [30].

As stated in Bril El-Haouzi's HDR [29], if literature is rich in studies related to the impact of humans on processes (for instance operational safety [152]), or vice versa (ergonomics [86]), these human aspects are however rarely considered in the design of control architectures for complex-adaptable systems [28, 30]. The emphasis is generally placed on solving technical problems, and developments remain mostly techno-centric. When humans are considered, it is to be included in the control loop, *a posteriori*, when the situation deteriorates or in the face of an unforeseen element [95]. This created situations where the human operator was given the "duty" to guarantee the systems' functioning by alternatively being considered as a robot in an ideally functioning system and as a magical being in a failing system,phenomenon called "Magic Human" [191]. As consequences, human agents were brought to face physical or mental overloads, lowering their situational awareness, etc. perturbing the completion of their tasks and the global system itself.

Hence, even though cooperation between human and technological entities has been widely studied, especially in air/rail traffic control [75, 203], applied robotics [71], or carpooling [147], previous statements highlight the importance that has been taken by technological aspects into IMS field, notably concerning holonic, hybrid and product-driven systems. This importance will keep growing with the rise of Industry 4.0 and of its supportive technologies. Industry 4.0 have brought new challenges to the global manufacturing landscape, both concerning technological and social issues. In this context, this Ph.D project aims to facilitate the design and implementation of holonic control architectures for manufacturing systems, in a way that meets their current and future socio-technical requirements. Hence, two questions have been explored in the first place:

- [QR1] How to take advantage from the new concepts introduced by Industry 4.0, such as the IoT and CPS paradigms, for the development of future manufacturing control architectures?
- [QR2] How to get the human better integrated in future manufacturing systems, as socio-technic ones?

The particularity of this Ph.D thesis project was the fact that it took place within a company 10 years after a previous one, also supported by the CRAN laboratory, having studied the implementation of an active Kanban system. For 80 years, the company had for historic mission to design, produce and sell particle-board kit furniture. Due to the emergence of European and global market players such as IKEA, the furniture market changed a lot for the last decades. Historical small and medium-sized companies were, and are at some point still facing new issues brought by factors such as emergence of e-commerce or diversification & raise of consumers requirements in terms of time, price, and quality. Hence, mass customization [144] has become ubiquitous where it was at first limited to sectors such a automotive industry. And while these new modes of consumption are implying new production methods, the production tools of manufacturers were still sized for the production of large series of undifferentiated products, therefore making them inadequate to fully meet their market.

Considering this situation, the previous Ph.D proved the need for this company to conciliate the centralized and predictive approach of traditional control architectures with the reactive and adaptable approach of distributed ones through the deployment of hybrid control architectures. To enable centralized/distributed decision-making system interoperability, this first project focused on the development and instantiation of an active Kanban system as the key to achieve the hybridization of control modes [90]. This work was part of a series of others dealing with the implementation of the Product Driven System (PDS) paradigm between 2007 and 2015 [135, 49, 110, 66]. These works were intended to provide the proof of concept for the paradigm of hybrid/decentralized control architectures as the key to manufacturing systems' interoperability, appeared in the early 2000s [120].

To better understand industrial issues, the first year of the Ph.D has been focused on physical and informational flows analysis. Concerning physical flows, their complexity was related to the multiplicity of workshops' specific know-hows, their interdependencies, and the variety of the product mix and supply modes. The main production site, presented by figure 1.2, was organized into 3 Autonomous Production Units (APU). Each of these had its own particle board stock, but only 2 of them were equipped with packaging lines, forcing the third one to delegate this final operation. Besides hardware and polystyrene dunnage were delivered and prepared into a fourth unit, supposedly supplying the packing lines in a timely manner. Two other specific production units were producing specific Medium-Density Fiberboard (MDF) or coated parts according to the needs of the other 3 ones. All finished products were grouped in a high-rise stock from which orders were prepared and shipped. In addition to that, each complete furniture was composed of 1 to 5 packages, each containing from 2 to 12 parts, not necessarily produced nor packaged into the same APU, for a total of 3 500 active packages references, either made-to-order and made-to-stock based on forecasts, for lot sizes from 150 to 2 000 units. Finally, it must be precised that last minute load shedding was a common practice to cope with unexpected event/disruption, and was the source of many disturbances in workshop flows.

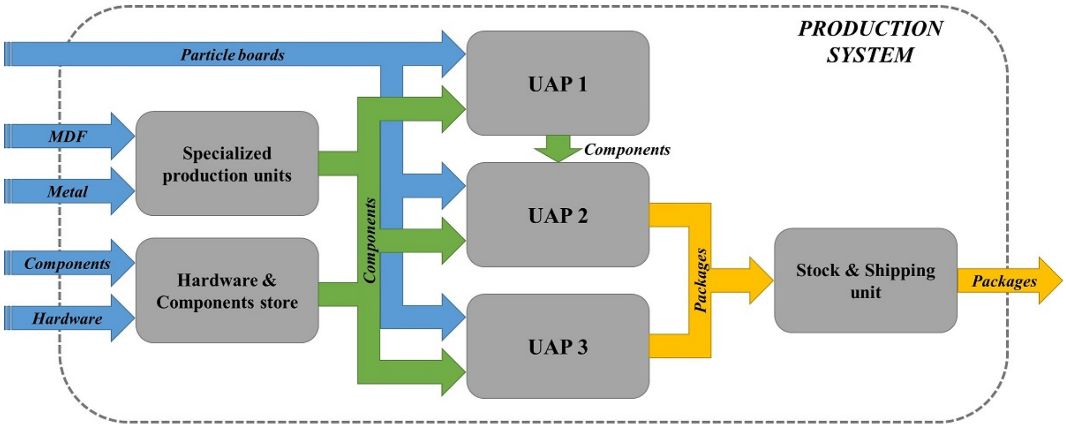


Figure 1.2: Main physical workflows

Concerning informational flows, the information management system was presenting a great disparity of software and versions, as well as some partitioning of these, negatively impacting the company's production planning and management system. For instance, due to historical changes, 3 Enterprise Resource Plannings (ERPs) were to be simultaneously found. Notably, trade, sales and shipping services were covered by an older version of the ERP used for production management activity, while a 3$^{\text{rd}}$ one, developed in-house, is today used as both a gateway to activate certain specifically developed software functions and an archive. Overall, all the software tools of the company, whether dedicated to stock, shipping, design, technical design, forecast, sells, planing, etc. management were all interconnected, yet not associated to any central software tool nor database. This situation had many implications. For instance, modifying one of these tools was requiring the destruction and creation of numerous data transfer and replication links between software. Consequently, the lack of a consistent and efficient IT tool was making it difficult to ensure the reliability of data, as well as communication between software and therefore between services.

Besides, numerous good practices, know-hows and procedures had been lost over time, impacting either global and local managements, and making inoperative many decision-making links, feedback loops, or leading to multiple out of sync data duplication. This complexity of both physical and informational flows, inherited from the historical, geographical, technological, and economical history of the company were heavily weighting against a centralized management mode. Consequences of this situation were multiples at all levels: lack of overall traceability of components, parts and finished products, difficulties to control the levels of work in progress within workshops, inability to manage finished products' stock level, lack of flexibility and of resiliency, insufficient customer service rate, etc.

This industrial context was raising many various issues, either related to the management of both physical and informational flows, production planning and control, decision-making, or skills and knowledge management. Initially, the project was part of a global rationalization and restructuring process. The approach adopted consisted of consolidating previous work, having focused on the hybridization of control modes through the Product-Driven System (PDS) paradigm, by implementing methods such as Jidoka, Just-in-Time, or QRQC (Quick Response to Quality Control)[185, 11]. The purpose was to empower the operators to change the focus from a product-centered to a more human-centered paradigm, thanks to the combination on both industrial and scientific methods.

This approximately 1 year-long immersion period within the company has in particular been the opportunity to study its Manufacturing Execution System (MES), deployed as part of Klein's works [90]. A "MES" is destined to ensure the integration between centralized (i.e. ERP, APS, etc.) and automated systems through the implementation of 11 functions relating to the management of technical information, and through the standardization of methods and information systems[3][4]. Its functions were to collect and store production data to enable products' genealogy and traceability, quality management, and performance analysis. To assess the quality of the data present in the system, the records covering the 23 past months have been analyzed according to criteria such as consistency of theoretical, calculated, and declared/recorded production cadences and times, or comparison between declared and counter quantities, etc. It quickly became apparent that the quality of the data was very uneven from one workstation to another. These gaps have been identified as being due to, on the one hand, inadequacy between the MES and the physical system, and on the other hand to human operators' errors. Inadequacy between the MES and the physical system was mostly related to the fact that the MES was initially internally developed for another production site of the group, and was implemented as is, despite its incompatibility with the management mode of certain workstations.

Concerning human operators' errors, the Generic Error Modelling System (GEMS) represented on figure 1.3 exposes 4 types: *slips*, *lapses*, *mistakes*, and *violations*. *Slips* can be related to the fact that operators can not see the point of what their actions, *lapses* to a lack of attention, *mistakes* to a lack of formation, and *violations* to a will to hide reality. Thus, the study of the MES made it possible to determine that the resolution of its problems had to go through the re-study of the adequacy of the current system with industrial needs and human capacities. This would consist in adapting the MES to the characteristics of the physical system, showing the operators the concrete results of the actions they carry out, setting up regular and thorough monitoring, and training them.The hindsight of this first immersive year within the company, has allowed to validate both the needs for an efficient manufacturing control, and for an human-centered approach. However, this project has been undermined by the judicial liquidation of the company, and the breach of the collaboration contract which ensued. On the strength of these industrial

[3] Manufacturing Enterprise Solutions Association (MESA):`https://mesa.org/`

[4] ANSI/ISA-95.00.01-2010 (IEC 62264-1 Mod) Enterprise-Control System Integration - Part 1: Models and Terminology:`https://www.isa.org/products/ansi-isa-95-00-01-2010-iec-62264-1-mod-enterprise`

observations, and regarding the company's economic situation, it has been decided to focus this Ph.D project on more academic modeling methods, dealing with complex adaptable systems, rather than studying the relevance of industrial field-approaches such as QRQC or Lean previously evoked.

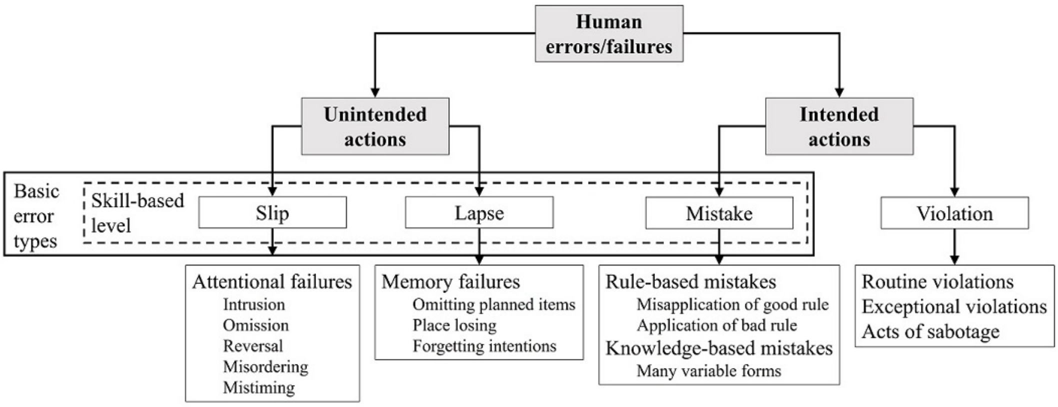


Figure 1.3: Generic Error Modelling System (from [152])

1.2 Scientific Background

1.2.1 Control architectures: an overview

Control systems are in charge of managing, commanding, directing or regulating the systems being subject to them. According to the ASCM[5]'s APICS[6]' dictionary[7], a manufacturing control system is defined as "*a system that has its primary function the collection and analysis of feedback a given set of functions for purpose of controlling the functions. Control may be implemented by monitoring or systematically modifying parameters or policies used in those functions, or by preparing control reports that initiate useful action with respect to significant deviations and exceptions*". Concerning the control activity, it consists in dynamically providing relevant instructions to a disturbed system, to reach a given objective, described in terms of performances control [187]. A control system is called *centralized* if it contains only one decision-making entity, and *distributed* if it contains more than one decision-making entity.

Traditionally, distributed control systems are classified as *hierarchical* or *heterarchical.* Decision modes divided into 4 classes: centralized (**Class 0**), pure hierarchy (**Class I**), heterarchy **Class II**, pure heterarchy (or isoarchy - **Class III**) (see figure 1.4). When detailing this classification, Trentesaux pointed out its genericity through 2 aspects: (1) the variety of possible layouts for Class II control modes, and (2) the fact that it is established based on the presence/absence of exclusively heterarchical/hierarchical relationship [188].

Concerning the 1st point, analyzes from Pach, Cardin et al. have led to proposition of a classification for Class II architectures, based on their structure dynamics and control homogeneity (Table 1.1). First type presents a Class II Static structure and a Homogeneous control (II-SHo): a high-level entity establishes global/long term schedule for low-level entities, whose are able to observe their environment and ask for recalculation when facing perturbations. Second type presents a Class II Static structure and a Heterogeneous control (II-SHe): a high-level entity establishes global/long term schedule for low-level entities, whose are able to locally change it when facing perturbations, through negotiation mechanisms for instance. Third type presents a Class II Dynamic structure and a Homogeneous control (II-DHo): in case of perturbation, the whole control mode switches from hierarchical to heterarchical mode. Fourth type presents a Class II Dynamic structure and a Heterogeneous control (II-DHe): control mode switches only applies to entities facing/concerned by perturbations [134, 35].

Table 1.1: The 4 types of hybrid control architectures [134, 35]

		Structure	
		Static	Dynamic
Control	Homogeneous	[132, 183, 133, 42, 22]	[73, 139, 112, 217, 192, 154]
	Heterogeneous	[129, 151, 24]	[100, 224, 198, 18, 134, 74]

Concerning the 2nd point, one could imagine other relationships than heterarchical/hierarchical

[5]ASCM: Association for Supply Chain Management
[6]APICS: American Production and Inventory Control Society
[7]APICS Dictionary: https://www.ascm.org/learning-development/certifications-credentials/dictionary/

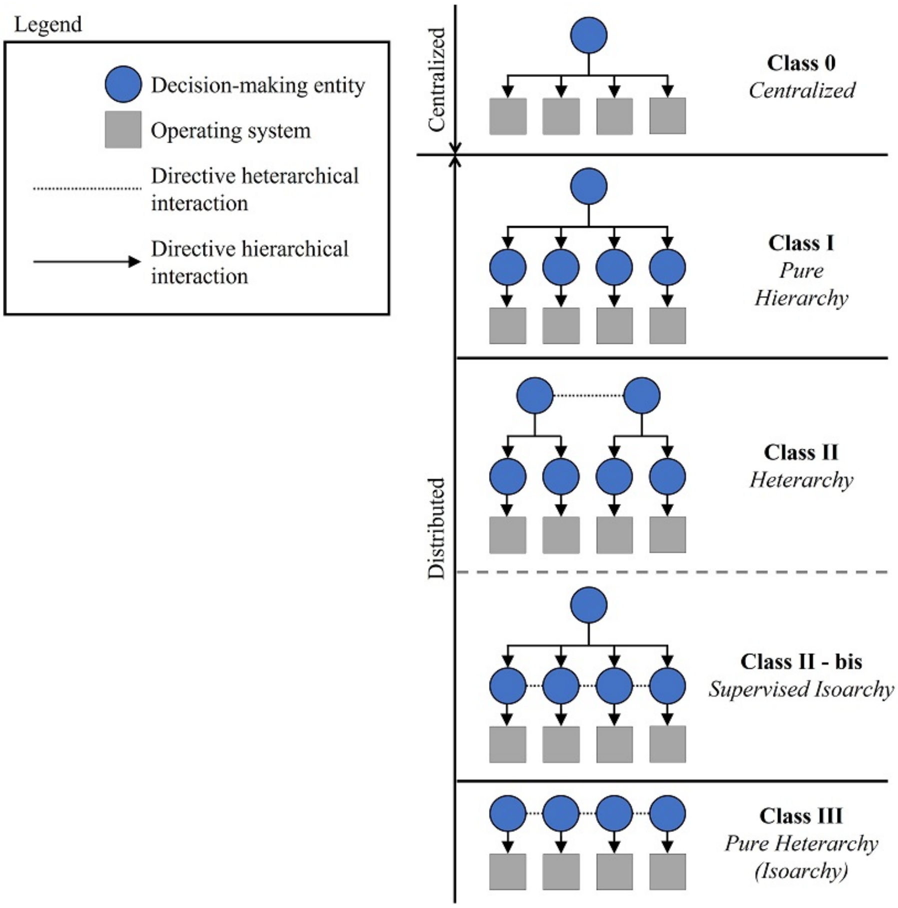


Figure 1.4: Illustration of control modes (based on [188])

ones. If the previous point was bringing enhancement to the classification by detailing Class II control mode, adding other relationships would in fact consist in creating other side typologies, ones for each relationship type. Developing these typologies are not the scope of the present Ph.D project, but would constitute a logical extension to the social relationship's typology that will be proposed in the next sections.

1.2.2 Holonic Control Architectures

Regarding the CRAN's works, the PDS control mode has commonly been studied through the holonic paradigm prism. Holonic Control Architectures have notably been the subject of two extensive literature reviews led by Cardin, Derigent and Trentesaux between 2018 and 2020 [34, 45]. These works have identified, studied, and classified reference HCA developed from 1998 to 2020, on the basis of their contribution to future industrial challenges (figure 1.5) [202, 194, 85, 99, 148, 96, 134, 62, 84, 204, 18, 77, 33]. To these, have been added some more recent works, posteriors to the reviews: the REDCA and EMH^2 architectures [56, 117] and the holonic reengineering for CPS [111] propositions. From this first sample, 3 observations could be made:

- First: for each of these propositions, implementation is achieved by transposing the holonic system into a multi-agent one, which seems common sense in computer sciences. The wide use of object-oriented modelling and of Java technology must notably be noted.
- Second: these approaches are seeking to define control architectures. The definition of an architecture is enabled by establishing both holons, and structuring elements relating them to each others called "relationships". Concretely, these are commonly not developed beyond the notions of aggregation, hierarchy, or data-exchanges. Formalism is rather rudimentary, based on a direct abstraction of the studied system's components.
- Third: Human or social dimensions are absent from these approaches.

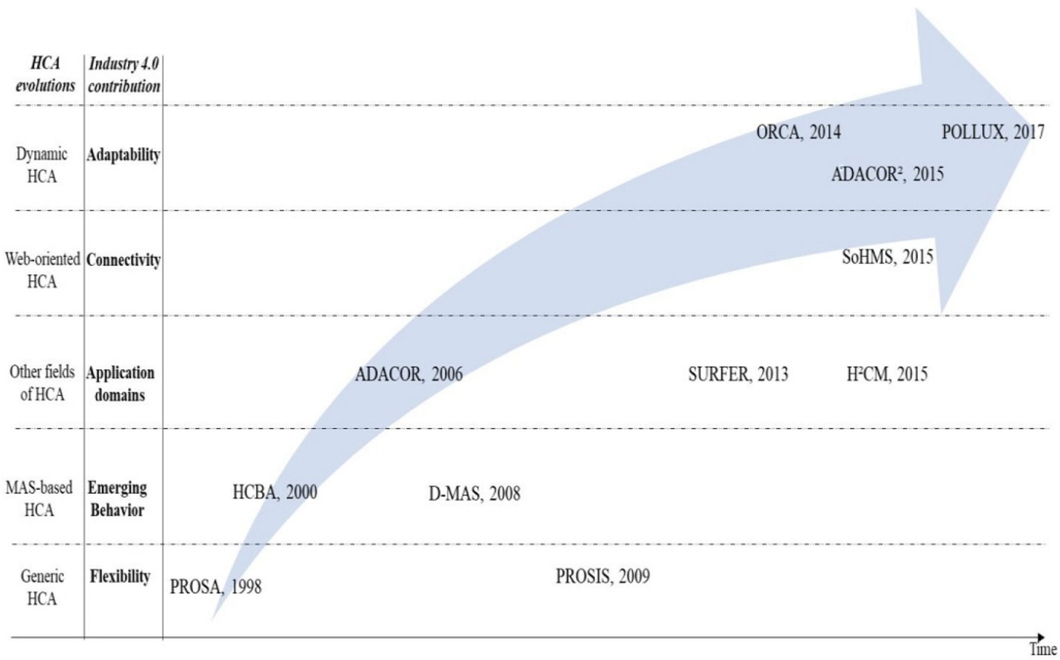


Figure 1.5: Evolution of HCA along time and their respective contributions to Industry 4.0 ([34])

To go further, the *Web of Science*[8] multidisciplinary bibliographic database has been searched with the *"(TS=(holonic AND (control OR architecture* OR manufacturing OR system*) AND (social OR human OR anthropocentric))) AND LANGUAGE: (English)"*, search-string. This search was targeting the documents having for subject Holonic Manufacturing Control or Architecture, considered with social, human, or anthropocentric point of view. Besides, the research is restricted to English-written journal papers, conference papers, books, and book chapters. This research has returned 110 results, spread from 1996 to 2020. Out of these 110 results, we have identified the 18 articles that seem the most pertinent after applying selection methodology similar to the SLR one. The analysis of this second sample, more heterogeneous for it is not focused on control architecture design, allowed more nuanced observations:

[8]Web of Science: `https://www.webofscience.com`

- First: this sample is way more conceptual than the precedent. However, for works proposing an implementation method, the use of object-oriented modelling and Java technologies, commonly used in Multi-Agent Systems (MAS) research field is once again observed. Yet, it is interesting to note that MAS are not only used for implementation: several of the identified works are explicitly using them to define all or part of their model.
- Second: these works being not seeking to define control architectures, the notion of "relationship" is there more diversified than in the previous sample. Notably, if notions of aggregation, hierarchy, negotiation, and data exchanges are still found, notions of cooperation, collaboration, and symbiosis are equally used.
- Third: since the keywords "Anthropocentric", "Human" and "Social" have been used in the search string, a greater consideration for human factor in the sample is necessarily observed. Here, it must be noticed that all papers are not dealing with its specific integration into manufacturing systems.

In the results analyzed, 5 distinct approaches can be identified. The first and most represented one mostly relies on techno-centered approaches for holonic systems destined to ease Human-Robot/Computer/System interfacing and cooperation [7, 94, 93, 76, 223, 159]. Between 1997 and 1999 has appeared a second more inclusive vision, where human agents were as much as possible considered as full-part holons within the holonic models for system or architecture design [3, 186, 179, 103]. At this point, an third approach, neither explicitly human nor social-related, draws attention: the transposition of biological structures & mechanisms to holonic manufacturing systems [170, 98]. From the implications of these is emerging the fourth approach: the addition of social relationships to enhance previous holonic developments and structure new HCAs, these relationships being either derived from works in sociology or based on social behaviors observed into, for instance, ant-colonies [197, 2, 52]. Finally, a fifth more recent philosophy can be identified, focused on Human-System Integration thanks to enhanced inter-agent interfacing and connectedness [23, 65].

1.3 Preliminary literature analysis

The first step in any research work consists in an analysis of the literature. This analysis must initially make it possible to broaden the subject in order to apprehend as much as possible the ins and outs of it. During this step, the subject can be adjusted, its relevance assessed, and research axis identified. Then, a second iteration of literature review has to be conduced to rigorously explore the research axis and provide solid ground for development works. This section will present the first iteration of literature analysis that was performed during the Ph.D project. Second iteration will be the subject of the next chapter.

From what was presented in previous sections, the project is focused on the development of an anthropocentric (or human-centred) approach for manufacturing systems' hybrid control architectures. Roughly, 2 poles can be guessed: *human aspect* and *hybrid control*. Starting from these 2 poles, Klein's work, and the scientific base of the laboratory, and through the systematic search of concepts' paternity, grounding works and similar developments, a consequent amount of references have been retrieved. Besides, participation in several conferences and workshops, along with the redaction of conference and journal articles eventually enriched this first work basis. To gather the retrieved documents, a bibliographic matrix has gradually and manually been established, regrouping in its final version 441 documents from 1948 to 2020. In this matrix have been indexed, when applicable, the documents' nature (journal article, conference paper, book, book chapter, PhD thesis report, technical report, etc.), publication year, title, authors, keywords, abstracts, and publisher.

The idea was then to analyze this empirical search to get a clearer view of the research fields and axis associated to the subject, and to identify the relevant keywords to perform the second literature review iteration. This analysis had to be performed using the VOSviewer software tool[9], that enables constructing and visualizing bibliometric networks, either based on authors or keywords. Hence, to strengthen the bibliographic mapping, documents with no explicit keywords (elderly papers, books, some PhD thesis, etc.), were given one or two, based on their title and abstract when possible. For instance, the paper "*Suggestions for a Sociological Approach to the Theory of Organizations - 1*" from T. Parsons [138] was associated to the keywords "*THEORY OF ORGANIZATIONS*" and "*SOCIOLOGY*". Documents for which these elements could not all be attached were consequently excluded from the mapping. Hence, out of the 441 documents referenced by the matrix, 436 have been used to establish the bibliographic cartography, with 940 unique keywords (1.630 with duplicates). Figure 1.6 presents the resulting keywords-based map. For the sake of clarity and readability, and after several iterations, only keywords presenting more than 4 occurrences are used.

Based on this cartography, 3 intersecting groups of keywords have been identified, and consequently established as the 3 poles to be explored by the project, presented on table 1.2. Yet, if this mapping duly allowed to identify research axes, it shows limits biases that make its further exploitation undesirable. Even if a while producing a significant effort of objectivity during the literature review, the very nature of the exercise induces a great deal of subjectivity. This subjectivity associated with the richness and different biases of publication, access, or evaluation of current literature tend to make any analysis imperfect, regardless of the method used and the time & energy invested. For instance, the keywords upon which the cartography is built, are often defined accordingly to the scope of their target conference/journal/audience, and selected

[9] VOSviewer: `https://www.vosviewer.com/`

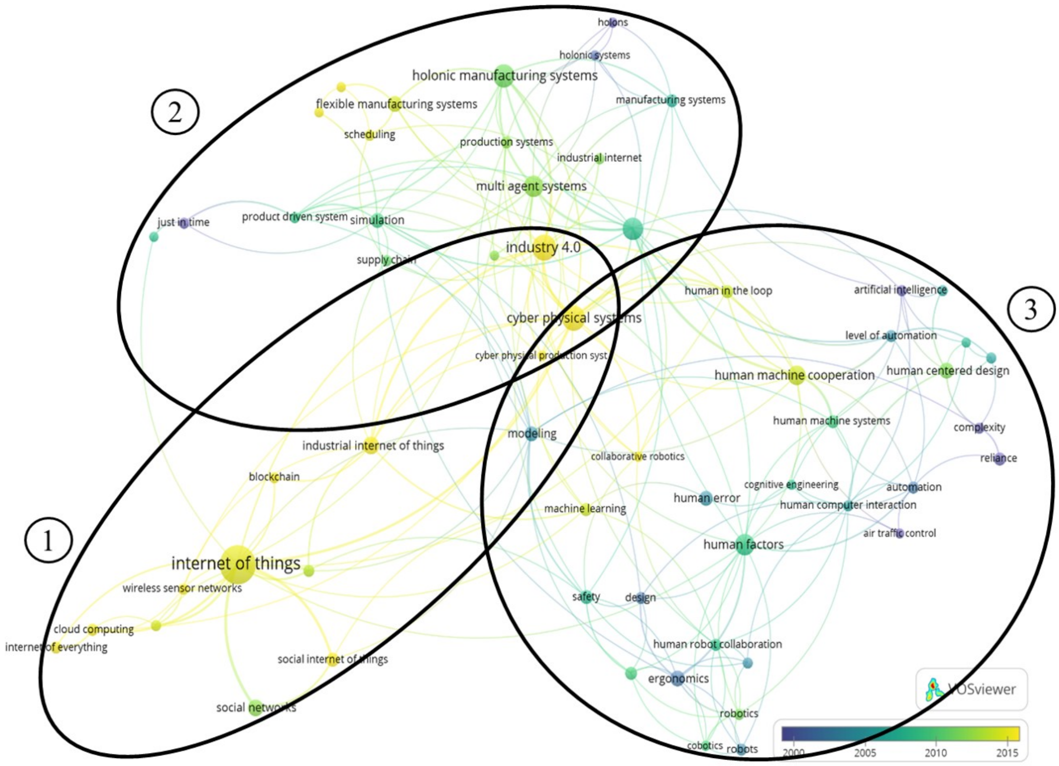


Figure 1.6: Keywords mapping for initial search

from a pre-established list. Consequently those are not always perfectly reflecting the paper's scope, nor sufficient to express all the aspects and research fields covered. Equally, the mapping is established on a number of co-occurrences, and on the interconnections between keywords from a document to another. Consequently, relevant keywords might have been excluded from the mapping, due to a lack of interconnection with other ones. For instance, the expression "*Cyber-Physical Social System*" which is significantly occurring in bibliographic matrix, is either not related to the keyword "*Cyber-Physical Systems*", nor to any of the keywords comprising the term "*Social*", however numerous.

Thus, regarding table 1.2, the following keywords have been retained for further search strings elaboration. Concerning "Manufacturing Control" pole, the 3 concepts of *Holonic Control Architecture*", "*Hybrid Control Architecture*", and "*Multi Agent System*" seemed to be the most suitable and relevant tracks to deepen. Concerning the "Industry 4.0" pole, the 2 main pillars that we have been able to identify as promising for the development of our research are the "*Internet of Things (IoT)*" and "*Cyber-Physical Systems (CPS)*". Different approaches to Industry 4.0 have established their own identifications of the supportive technological groups for Industry 4.0 [156]. Among these, the *IoT* and *CPS* were particularly standing out as main pillars for Industry 4.0. *Big Data*, *Cloud Computing*, *Simulation*, *Virtual Reality*, *M2M Communication & collaborative robots*, or *Cybersecurity* being overall considered as more generic technologies/stakes, to be considered within the IoT and CPS frameworks. Finally, the "*Human Aspect*" pole: the human being is a complex subject which has many aspects. In order to remain as general as

Table 1.2: Identified research poles and main keywords

Pole "Industry 4.0"	Internet of Things (IoT) Cyber Physical Systems (CPS) Industrial Internet of Things (IIoT) Cyber Physical Production Systems (CPPS) Social Internet of Things (SIoT) Social Networks
Pole "Manufacturing Control"	Production Systems Manufacturing Systems Intelligent Manufacturing Systems (IMS) Flexible Manufacturing Systems (FMS) Multi Agent Systems (MAS) Holonic Manufacturing Systems (HMS)
Pole "Human aspects"	Human-Centered Design (HCD) Human-in-the-Loop (HitL) Ergonomics Human Error Human-Machine Cooperation Human-Robot Collaboration Human-Computers Interaction Human-Machine Systems

possible, going down to "psychological", "physiological", "cognitive" levels has been avoided, in favor of the more generic "*Human-centered*", "*Human-inspired*", and *social* notions.

The 3 poles exposed here above are then framing and structuring this research project. However, due to their broadness, those can naturally not be individually in-depth studied. Concerning the *Manufacturing Control* pole, Pach, Cardin, Trentesaux et al. have already provided the rather recent and extensive reviews on the subject, that are detailed here above. Besides, in accordance with the human-centered aspect of the issue, the *Industry 4.0* poles has been studied regarding the *human aspect* one. Equally, through the convergence of these concepts and notions, the following hypothesis is proposed to answer the questions stated above:

Establishing a reference framework for the design and implementation of manufacturing systems' control architectures, based on Industry 4.0's main assets, would ease the integration of the human factor into them, and help them meet their current and future challenges.

1.4 Dissertation organization

This chapter has presented the Ph.D project's industrial background, and its integration in the continuity of CRAN laboratory's last decades works. Industrial issues and scientific context have been exposed, showing the need to head toward human-centered conception for control architectures to bring resiliency into current and future complex-adaptable industrial systems. Notably 2 questions have been established, that have been guiding the rest of the project' works. A preliminary literature analysis have equally been conducted to validate the placement and orientation of the research work. The rest of the dissertation is organized as follow.

Chapter 2 will expose the Systematic Literature Review (SLR) that have been conduced to question the place given to humans within the global framework of Industry 4.0, and more particularly regarding CPS- and IoT-based literature. It will study integration of industrial systems' actors as a global networks of interconnected assets (artefacts & humans, objects & agents) within complex-adaptable systems from both an industrial (Industry 4.0 and 5.0) and a systemic frameworks (complex systems). Additionally, this section will establish a typology for the sociability types and the different kind of social systems that are commonly retrieved in literature.

Chapter 3 will present the main contribution of this project. The idea will be to propose a reference framework for social holarchies modeling, based on an evolution of traditional holons' representation, where human-inspired social character is added to their classic coordination mechanisms. More precisely, the use of an human-inspired social relationship typology will be proposed, in order to go beyond the classical hierarchical, heterarchical, or isoarchic structuration. The hypothesis will be that, a social approach might ease the design and implementation of future human-adapted HCA into actual manufacturing systems, as well as their understanding and consequent acceptability by human agents. Hence, a definition of these social relationships and formal framework will be proposed, along with a modeling and visualization software tool.

Chapter 4 will bring the proof-of-concept for this new approach, thanks to CRAN's TRACILOGIS test-bed platform. The social model will notably be instantiated for 3 different control modes, thanks to 3 scenarios. The chapter will therefore begin by providing a description of the TRACILOGIS technical platform, its components, and control modes. Then, it will assess the proposed modelling framework by applying it to the beforehand defined control modes. Finally, it brings a discussion on the contribution of this framework reduce models' perceived complexity thanks to aggregation capacity.

Chapter 5 will bring a general conclusion and a discussion regarding this Ph.D thesis' works, along with outlooks on the potential of this work, as well as on avenues for future development.

Chapter 2

Literature Review

2.1 Chapter introduction

For the last decade, the initiative Industrie 4.0 [1], along with number of other national programs (Industrie du futur, High Value Manufacturing Catapult, Made in China 2020, etc.) have been taken as reference background for the development of industrial systems. By their impact, these initiatives are today commonly recognized as part of the 4^{th} industrial revolution, also known as *Industry 4.0*, and globally responding to the same precepts [220]. Initially, Industry 4.0 was aimed to "*address and solve some of the challenges facing the world today such as resource and energy efficiency, urban production and demographic change*" [1]. From an industrial viewpoint, the most important challenge – and maybe the easiest to apprehend, might be to head towards continuous resource productivity, and efficiency gains delivery across a globalized value network.

To deal with demographic and social changes, Industry 4.0 have raised the attention on the need to rethink work organization. For instance, facing skilled workforce shortage, industries need to preserve their workers to extend their working lives, and to keep them productive longer. To this end, research on systems, such as smart assistance ones, have known a consequent growth. Notably, the recent appearance of the *Operator 4.0* concept, proposing a vision for human-automation symbiosis by enhancing "*human's physical, sensitive and cognitive capabilities by means of human cyber-physical system integration*" [155], can be evoked. These systems are designed to release workers from routine, wearing or dangerous tasks, to refocus them on creative and value-added activities. Besides, these developments equally aim to support flexible work organisation that, beyond being resilient, would enable workers to better combine their work and private lives, improving their work-life balance. Hence, it can be assessed that, in its initial conception, Industry 4.0 was destined to address and solve both technical and societal challenges, relying on last decade's technological advances concerning Internet of Things (IoT) and Cyber-Physical Systems (CPS). This led to the rise of the debate around new *Work 4.0* paradigm in Germany [212], questioning the societal implications of Industry 4.0 into everyday work. Yet, it is today assumed that Industry 4.0 have stayed focused on CPS- or IoT-based general purpose technologies (technology-driven progress), somehow missing its societal scope.

To influence this dynamic, recent years have seen the appearance of a new paradigm, proposed as a societally-driven complement to Industry 4.0's hallmark features: the Industry 5.0. Broadly, Industry 5.0 can be seen as a corrective "patch" or "add-on" to the Industry 4.0, focusing on human-centric design, sustainability, and resilience. That is not to say that the technology is out of scope. Emphasis will be placed on technologies as a set of complex systems, combining technologies such as smart materials and embedded / bio-inspired sensors, enabling, securing, and strengthening human safety, well-being, and interactions into and with the industrial system, such as Augmented or Virtual Reality, collaborative robotics, etc. To this end, recent works of the [53, 55], involving European Union's technology leaders, proposed a set of relevant and enabling technologies for Industry 5.0. Besides, the reports from European commission [53, 55] equally point out the fact that a systemic approach for Industry 5.0 is necessary to support the above-mentioned technological enablers. Indeed, Industry 5.0 and its technologies are expected to face the social, ecological, economic, governmental and political challenges, left aside by Industry 4.0. Consequently, with regard to the industrial community research fields, the challenge is to strengthen human's trust and acceptance concerning those new technologies, developing inter- and trans- disciplinary in future works (to make engineering, life & social sciences, humanities, etc. converge), and ensuring their broad-scale implementation across value chains and ecosystems (scalability).

This chapter proposes a Systematic Literature Review (SLR) focusing on the global integration of industrial systems' actors as a network of interconnected assets (artefacts & humans, objects & agents) within complex-adaptable systems [30]([QR2]). Notably, what will be studied is the place given to the human component by the new concepts introduced by Industry 4.0, such as the IoT and CPS paradigms, to identify their potential for more human-centred hybrid control architectures' development ([QR1]). Therefore, the purpose is to provide a picture of current engineering trends and technological enablers for Human System Integration (HSI), by bringing together the 3 *human*, *CPS* & *IoT*, and *industrial* aspects.

To this end, the rest of the chapter is organized as follow. 2$^{\text{nd}}$ section will provide an definition and global overview of the notions of IoT and CPS concepts, in order to contextualize them within Industry 4.0. Then, the 3$^{\text{rd}}$ section will detail the methodology used to perform the SLR, based on Kitchenham's methodology [88]. In the 4$^{\text{th}}$ section, the literature retrieved thanks to this methodology will be the subject of a first general analysis, focused on quantitative aspects. This section also contains observations concerning 3 forms of sociability structuring 4 types of social systems, that can be made when taking a closer look to place of human aspects into IoT and CPS research. Then, 5$^{\text{th}}$ and 6$^{\text{th}}$ sections are conducting qualitative analysis on the retrieved literature through 2 specific frameworks: Industry 5.0 and Systemics. Last section concludes the chapter and proposes some research directions.

2.2 IoT and CPS: an overview

The importance of the CPS and IoT concepts have steadily been growing in the literature for the last decades (Fig. 2.1). The notion of CPS is generally recognized as the main pillar of Industry 4.0. Due to its wide range of potential applications, this concept enjoys great popularity in the scientific literature although it is rather recent [97]. However, popularity and novelty make it a concept whose definition and limits are rather blurred. Besides, it is also often associated with the IoT, which appeared a little earlier. It seems that preferences in the use of the terms CPS and IoT are observed from one scientific community to another or from one geographical area to another. Thus, CPS will be preferred in mechatronics, and IoT will be preferred in computing societies [29, 25]. The term CPS will also be found more often on the American continent than on the European or Asian ones, where IoT will be preferred. However, these two concepts are in fact different and have to be differentiated.

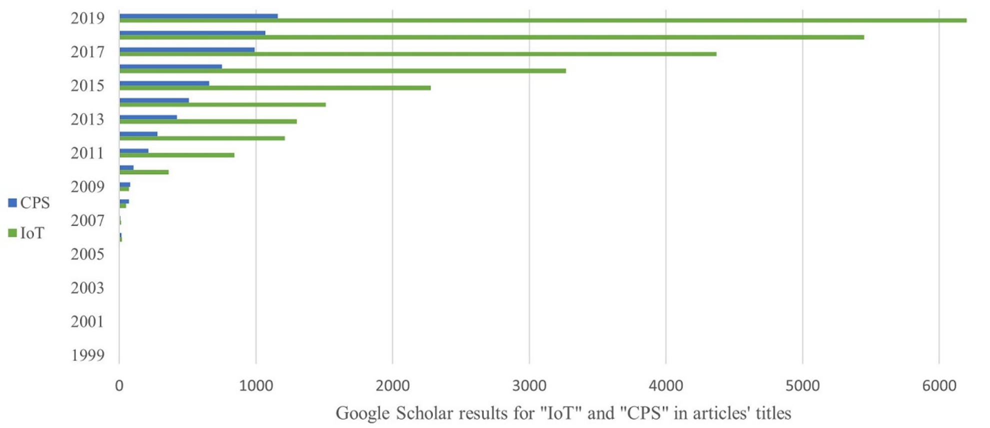


Figure 2.1: Results per year for terms "*Cyber-Physical System*" and "*Internet of Things*", in title only, with Google Scholar

According to Ashton [13], the IoT was first enunciated in 1999 to describe the lack of reliability of human-gathered Data that were flowing through the internet, due to human limits such as "*limited time, attention and accuracy*".It suggests the use of Radio-Frequency Identification (RFID) sensors and technologies to give computers the ability to gather their own Data from their environment (physical or informational). The 2005's Internet Report from the International Telecommunication Union (ITU) stays close to this definition, only enriching its enabling technologies with ones such as "*sensors, smart technologies (such as robotics and telematics), and nanotechnology*" [153]. From 2004, authors like Gershenfeld & al. have proposed concrete applications of the IoT, especially in the home automation's development context that they call "*Internet Zero*" (I0) (Fig.2.3). In this development, they get closer to a network-related definition than Ashton or the ITU, as they create a direct link between the Internet and the IoT thanks to the axiom: "*the original idea of linking computer networks into a seamless whole – the "Inter" in "Internet*" – can be extended to networks of all types of devices, a concept known as interdevice internetworking" [64]. Hence, the IoT's definition has evolved due to the "IoT" term's growing popularity into scientific research domain.

Among the multitude of definitions that can be found in the literature, we will retain the following: "*an open and comprehensive network of intelligent objects that have the capacity to auto-organize, share information, data, resources, reacting and acting in face of situations and changes in the environment*" [108]. In this definition, IoT is clearly seen as a link between physical objects within a system composed of multiple objects. Regarding CPS, it seems relevant to keep its initial definition provided by Lee: "*physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core. This intimate coupling between the cyber and physical will be manifested from the nanoworld to large-scale wide-area systems of systems. And at multiple time-scales*" [97]. The CPS concept therefore expresses a "coupling" between physical objects and their digital representation/twin. Considering these two definitions, we define a system as being composed of objects and their digital representations. This system is organized along 2 axes: the first one, representing the physical world; the second one representing the digital world (i.e. cyber). The IoT would then correspond to the horizontal connectivity/synchronization between objects and the notion of CPS would call the vertical connectivity/synchronization between objects and their digital representation [16] (Fig. 2.2).

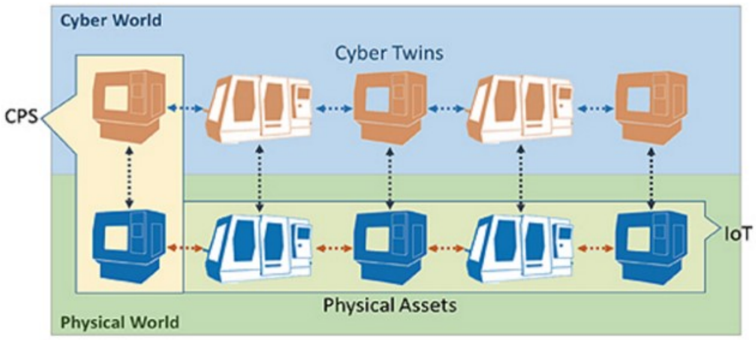


Figure 2.2: CPS & IoT [16]

Hence, it can be assessed that CPS and IoT are constituting the 2 of today's main enabling paradigms for Cyber-Physical Systems' networking, and then for Industry 4.0, relying on the integration of objects, their virtual representation, and humans, as networks within complex-adaptable systems. Yet, these visions stay techno-centered, focused on machine-machine interactions.

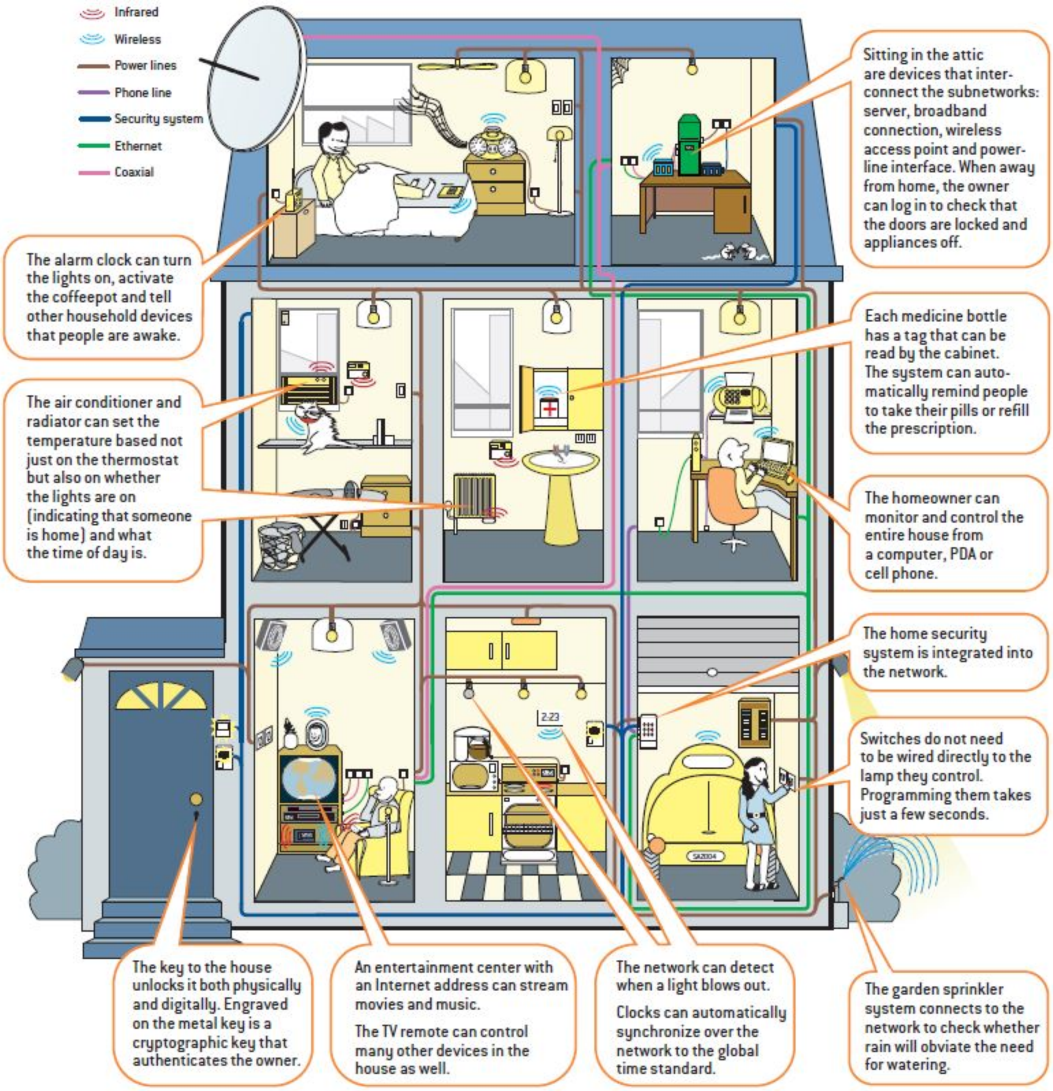


Figure 2.3: The Internet-Zero [64]

2.3 Methodology for Systematic Literature Review

This section will expose the research protocol, accordingly with the SLR guidelines provided by Kitchenham [88]. The SLR methodology will allow to provide the most representative possible state of the art concerning the *human dimension* in *CPS* and *IoT*-related paradigms regarding different *industrial* context. Note that the general *manufacturing control* pole identified in the introduction is not included in the scope of this search, for previous works that will be presented hereafter already provided extensive review of the subject. To ensure the quality of this SLR, the paper selection method has been established using the 4 following recommendations from the Centre for Reviews and Dissemination (CRD)'s Database of Abstracts of Reviews of Effects (DARE)[10] [89].

- Relevant search-string and at least 4 databases shall be used to cover most of the related works;
- Inclusion and exclusion criteria must be explicit and appropriate, ensuring the relevance of the study;
- Accordingly to a set of pre-established criteria, the quality and validity of included studies shall be assessed;
- Included studies shall be synthesized, with emphasis on their relevant data/contents.

To conduct this study, more than 10 scientific digital libraries and databases have been identified. Yet, after a first search iteration, some turned out to be unsuitable for a search strings-based targeted search, or for results mass-extraction. Ultimately, the 8 following databases and digital libraries were used for this study: ACM[11], BASE[12], HAL[13], IEEE Xplore[14], Science Direct[15], Scopus[16], Taylor & Francis[17], and Web of Science[18].

Search strings have been built based on 3 sets of keywords, each relating to one aspect of the search. The first one, searched by S_1, aims to review literature related to the CPS and IoT paradigms and their variants. To this end, the terms "*Cyber-Physical Systems*" and "*Internet of Things*" have been decomposed for more inclusion. The second search string, S_2, aims to limit the search to industrial context, using terms "*manufacturing*", "*production*" and "*industry*". The third one, is grounded on the keywords commonly used when considering the human aspect in literature, identified in previous studies [200, 50]: "*human*", "*anthropocentric*" and "*social*" (S_3). The search strings are presented below, formatted using Boolean logic, as usual for digital library querying. These were eventually adapted, to better suit libraries' particular specifications.

S_1 : "(internet AND of AND thing*) OR (cyber* AND physical* AND system*)"

[10] DARE: https://www.crd.york.ac.uk/crdweb/ShowRecord.asp?ID=32004000332&ID=32004000332
[11] ACM Digital Library: https://dl.acm.org
[12] Bielefeld Academic Search Engine: https://www.base-search.net
[13] Archive ouverte HAL: https://hal.archives-ouvertes.fr
[14] IEEE Xplore: https://ieeexplore.ieee.org
[15] Science Direct: https://www.sciencedirect.com
[16] Scopus: https://www.scopus.com
[17] Taylor & Francis: https://www.tandfonline.com
[18] Web of Science: https://www.webofscience.com

S_2 : "manufacturing OR production OR industr*"

S_3 : "human* OR anthropo* OR socio* OR social*"

The query R supporting this SLR will then be the association of S_1, S_2, and S_3. Consequently, the literature scan will consist in querying each of the bibliographic database previously listed with the following search.

$R = S_1$ AND S_2 AND S_3: "((internet AND of AND thing*) OR (cyber* AND physical* AND system*)) AND (manufacturing OR production OR industr*) AND (human* OR anthropo* OR socio* OR social*)"

The papers selection and exclusion process was carried out in 3 stages. First selection step occurred directly during databases querying, with the following criteria:

- To avoid papers with no close bound to the search, the string R was not used for a full-text search, but focused on papers topic i.e.: title, abstracts and keywords;
- English-written papers: for the sake of homogeneity, and to guarantee the international scope of the study;
- Timespan: 1990 - 2021, for IoT and CPS paradigms are no prior to 1999.

Second step was performed upon the aggregation of the results from initial search R into each database:

- Removal of duplicates;
- Removal of papers not consistent with initial research criteria;
- Removal of non-JCR publications. Only publications indexed to the Journal Citation Report(JCR), a reference framework attesting the quality of a journal, were targeted.

Third and last step was performed manually by the authors upon the remaining papers:

- Title, abstract & keywords analysis: removal of papers that are not closely related to the searched topic, and enables a first general analysis of the literature;
- Full-text reading: removal of papers for which an ambiguity persists, enabling an in-depth analysis of the literature.

In absolute terms, these two consecutive filtering shall be performed before any further analysis. However, full-text readings can only be performed on available documents, whose may turn out to be considerably fewer than those identified after the title-abs-key analysis. Moreover, considering the time required for the careful reading and understanding of a journal paper, this last step has to be conduced on an consequently narrowed amount of papers. For these reason, the general analysis of the literature was performed right after the title, abstract & keywords filtering, upon the metadata extracted from retained papers. Then, full-text reading and in-depth analysis were conduced upon the retrieved available papers.

2.4 General analysis

Table 2.1 presents the results of the query R for each one of the databases previously exposed. Figure 2.4 synthesizes the followed papers-retrieving methodology and its step by step results. Thanks to this selection process, the initial sample of more than 3 500 results was significantly reduced down to 149 exploitable bibliographic entries.

Table 2.1: Number of papers retrieved from each database

Queried databases	Results for R
ACM	91
BASE	42
HAL	49
IEEE Xplore	361
Science Direct	150
Scopus	1671
Taylor & Francis	7
Web of Science	1186
Total	3557

First noticeable thing is that, despite the fact that the search is covering a period from 1999 to 2021, only papers from 2011 to 2021 were retrieved. In addition, Figure 2.5 shows that a consequent and steady raise of interest could only be noted from 2016. It can therefore be assessed that the question of humans' place in CPS and IoT literature regarding industrial issues is rather recent, even thought those concepts are independently much older and studied.

Second, each contribution has been associated to the nationality of its authors' home universities. It then can be observed that around 40% of the retrieved papers are international collaborations. Besides, figure 2.6 reveals that China is by far today's main contributor, having produced or participated to more that 30% of current literature. Unsurprisingly, since this study is questioning the future of industrial systems, the others main international contributors being among the most industrialized ones (Spain, USA, UK, Germany, India, Italy, Canada, France, etc.).

Third observation concerns the journals represented by this sample. The 149 retrieved papers have been published into 84 different JCR journals, which is a relatively high number. Hence, 11 journals presents 3 times of more are representing 42% of the sample (Fig. 2.7). Most of these journals being related to industrial engineering, computer sciences, or technological research, those approaches can be stated as largely dominating the retrieved literature. For instance, the largely represented *IEEE Access* is relating to general engineering and computer & material sciences. Among the most represented ones, the *IEEE Transactions on Industrial Informatics*, *Computers & Industrial Engineering*, *Journal of Manufacturing Systems*, *IEEE Internet of Things Journal*, *Sensors*, *Future Generation Computer Systems*, *International Journal of Production Research*,or *Computers in Industry* journals can equally be cited. Nonetheless, several journals seems to be focused on more safe (*Process Safety and Environmental Protection*), sustainable (*Sustainable Computing-Informatics & Systems*), and human-centric (*Applied Ergonomics*, *Social*

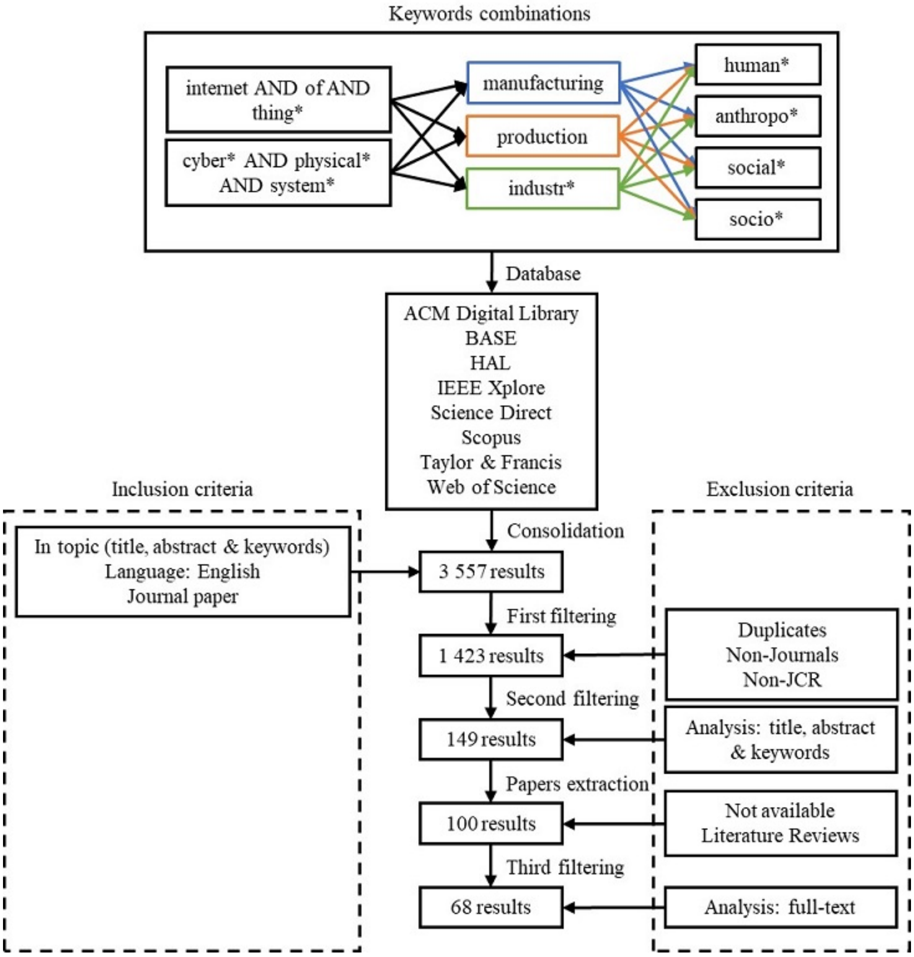


Figure 2.4: Papers retrieving methodology

Behavior and Personality, *International Journal of Human-Computer Studies*) developments.

The fourth and last element highlighted by this sample's analysis is the co-authorship among papers. Figure 2.8 is showing the result obtained using the VOSViewer bibliometric software to built a cluster network for authors having participate to 2 or more papers. Only 48 out of the 567 retrieved authors and co-authors proved to have participated to 2 or more papers. In addition, even if the interest for the subject is rising since 2016, the authors retrieved by the co-authorship mapping only published between 2018 and 2020. This globally denotes a rather new interest for the subject, led by small independent, yet international communities.

It can be summarized that research concerning the human dimension in industrial systems regarding the CPS and IoT paradigms has only recently become an important subject. Advances in this field are today notably supported by strongly industrialized countries, with great international cooperation. Yet, the subject is still emerging and the research community fragmented. Based on a first reading, more than 10 IoT and CPS variants can already be identified. Those variants can be considered as mostly differing by their application domain, enabling technologies, and

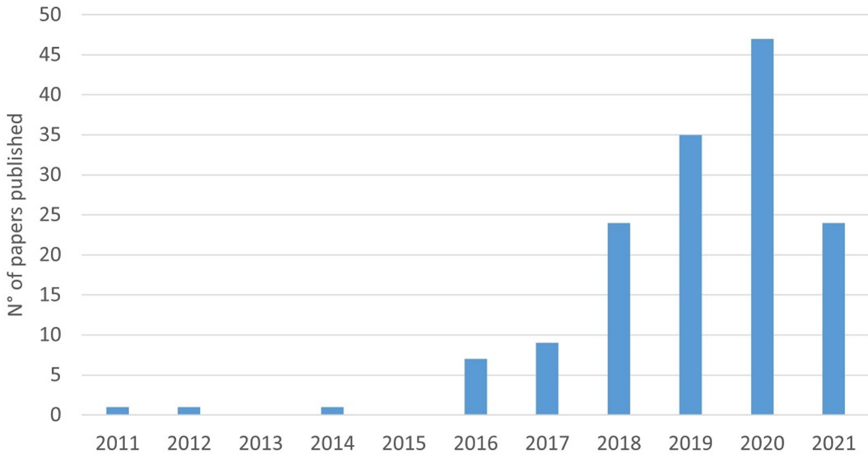


Figure 2.5: Number of papers published per year

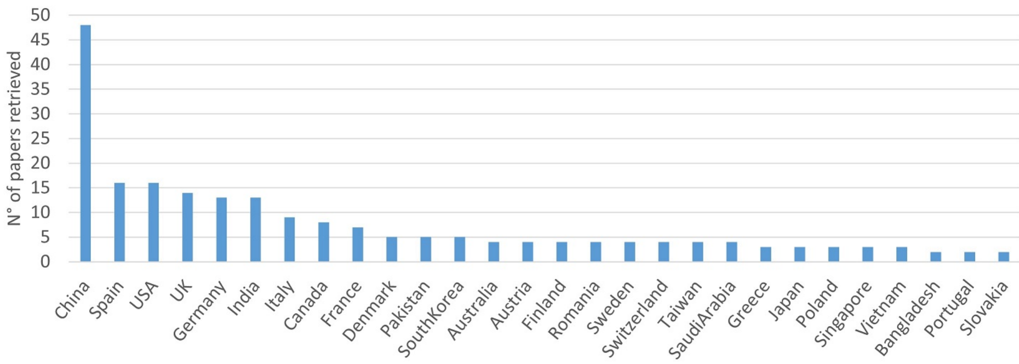


Figure 2.6: Number of papers published per country

system structuring & organization. Table 2.2 already summarizes the main characteristics of the most notable ones. Two aspects in these variants seem particularly relevant to study in this work. First, to characterize and analyze these systems' approach regarding the human factor, a systemic framework will be established and used. Then, the enabling technologies supporting these systems will equally be analyzed through a second framework. Next sections details these frameworks more precisely and will presents the result of the literature analysis through them.

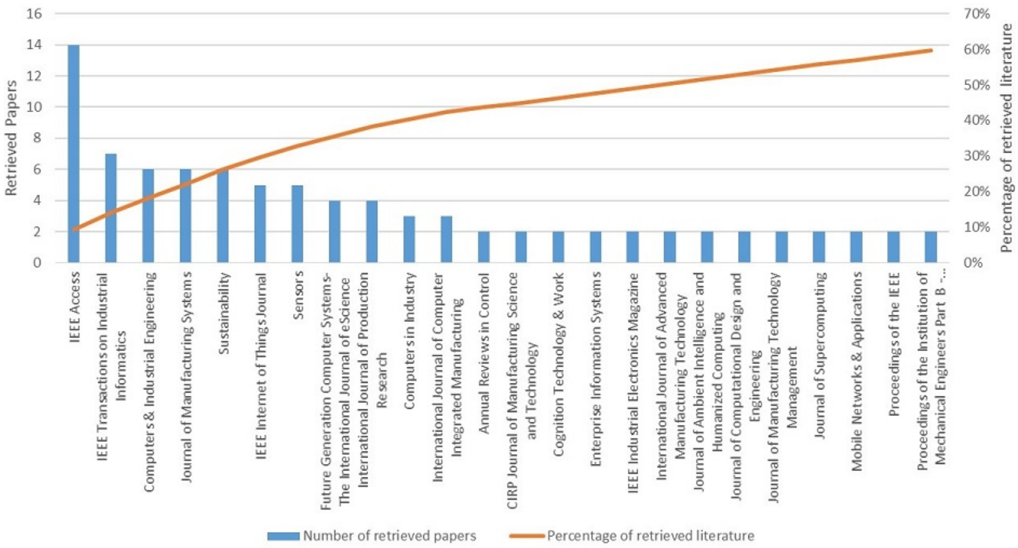


Figure 2.7: Journals representation in retrieved sample

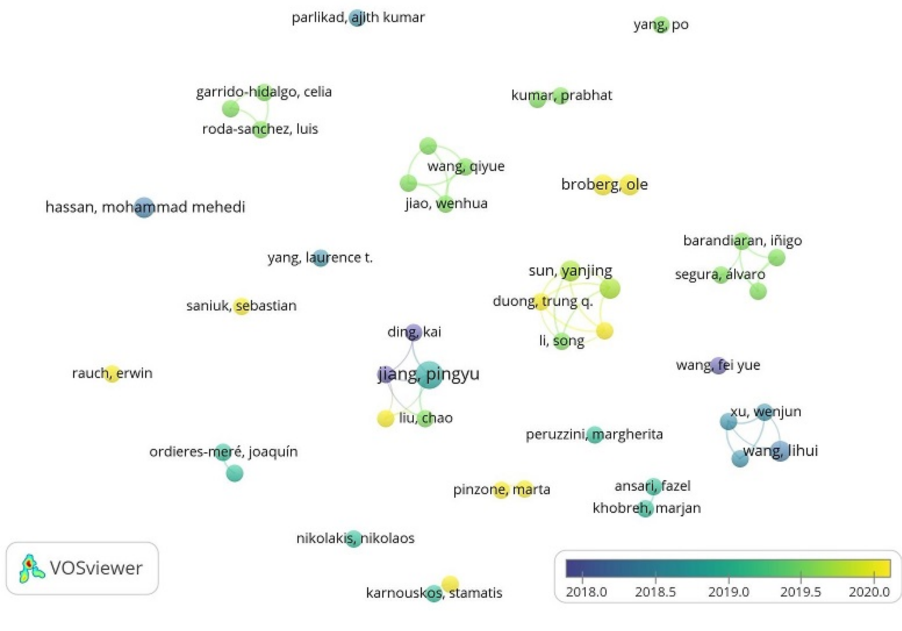


Figure 2.8: Co-authorship for the 48 authors with 2 or more publications

Table 2.2: IoT and CPS variants in retrieved sample

Term	Definition	References
ACPS	Anthropocentric Cyber Physical System: Reference model for factory automation integrating both physical, cyber, and human components.	[146]
CPHS / HCPS	Cyber Physical Human System/Human Cyber Physical System: Framework for smart manufacturing, integrating human, physical elements and cyber-technologies. Human cognition and learning are enacted by IoT devices to improve human-system interaction.	[190, 82, 38, 176, 180, 221]
CPIS	Cyber Physical Integrated Society: A society were cyberspace and real world are connected through networked IoT devices.	[173]
CPPS	Cyber Physical Production System: A system based on the progress of computer science, Information and Communication Technology (ICT), sensor and network technologies, including information systems and hardware resources, and supporting human-machine communication.	[106, 10, 9, 176, 178, 78]
CPSS / SCPS	Cyber Physical Social System/Socio Cyber Physical System: Integration of both social data, acquired from social networking platforms, and human data, acquired from sensors or human-system interfaces, into CPS.	[101, 46, 81, 220, 37, 221, 10, 115, 105, 216]
HitL CPS	Human in the Loop Cyber Physical System: In a smart factory context, a CPS were IoT development enables human performance integration, by measuring human cognitive activity through body and brain sensors.	[82, 221]
I CPHS	Industrial Cyber Physical Human System: Industrial systems in interaction with humans and complying with societal norms and expectations, including ethical aspects.	[190]
IoP	Internet of Persons: Persons location data acquired using Wi-Fi system logs, or any portable connected device.	[173]
S-HITL CPPS	Social Human-in-the-Loop Cyber Physical Production System: A human-centered manufacturing system framework where many agents collaborate and are socially connected at both physical and cyber levels.	[41]
SIoT	Social Internet of Things : A network of communicating objects/assets able to autonomously build their own structuring social relationships without human intervention. Those social relationships are coming from human social network services and media.	[31, 104, 40, 160, 101, 174, 177, 205, 211, 70, 206]
SIoIA / SIoIT	Social Internet of Industrial Assets/Social Internet of Industrial Things: Application of SIoT to industrial assets to reduce human inputs and then limit human-related disruption in the system.	[104, 70]
SM	Social Manufacturing: A cyber-physical-social connected and service-oriented manufacturing paradigm, where an IoT-based production structure delivers service-oriented transformations to a social network of prosumers.	[46, 81, 221]

2.5 Systemic and Technological analysis

This section details the analysis of the retrieved sample through 2 frameworks: one systemic, the other technological. Each of these analysis is supported by a graph presenting the research interest shown in the analyzed literature sample for each of the frameworks axes. It goes without saying that a publication can be related to several categories. The first analysis conduced onto the retrieved sample was intended to confront it to the 4 basic grounding concepts of systemics [47], namely *Complexity*, *System/Organization* (Table 2.6), *Wholeness* (Table 2.5), and *Interaction/Interrelations* (Table 2.4). Table 2.3 details more precisely these frameworks. The second analysis conduced onto the retrieved sample was intended to confront it to the technological enabling framework for Industry 5.0. According to the report from the [53], this framework is organised around 6 interrelated axes, namely *Human-centric solutions & human-machine-interaction* (Table 2.7), *Bio-inspired technologies & smart materials* (Table 2.8), *Real time based digital twins & simulation* (Table 2.9), *Cyber safe data transmission, storage & analysis technologies* (Table 2.10), *Artificial Intelligence* (Table 2.11) and *Technologies for energy efficiency & trustworthy autonomy* (Table 2.12).

Table 2.3: Systemic and Technological frameworks

Systemic Framework	Interaction/Interrelations
	Wholeness
	System/Organization
	Complexity
Technological Framework	Human-centric solutions & human-machine-interaction
	Bio-inspired technologies & smart materials
	Real time based digital twins & simulation
	Cyber safe data transmission, storage & analysis technologies
	Artificial Intelligence
	Technologies for energy efficiency & trustworthy autonomy

2.5.1 Systemic Framework analysis

Interaction/Interrelations

If, from a static viewpoint, a system can be defined as a set of interacting elements, then it can be deduced that the nature of a system emerges from both the nature of its component and the nature of their interaction. Concerning the *Interaction/Interrelations* concept, the notion of interaction focuses on the relationships between the elementary components of a complex system taken two by two. It can relates to influences or exchanges of matter, energy or information among system's components, the nature of these interactions being even more important to know than the one of the components themselves. More specifically, the study of the IoT and CPS variants presented by table 2.2 showed that human aspect integration into CPS and IoT systems was realized through different interaction or sociability models, ultimately aiming to ease the integration of human or any social systems into automated production systems [199, 30]. The first model is proposing interactive interfaces or embedded sensing systems to enable human-system interaction. The second one uses the structure of existing social network services, that are offering numerous features and data to establish a socialization-based internet. The last model relates to the design of an industrial system as a society, linking smart connected objects through a typology of social relationships. Thus, the 3 following types of sociability can be identified:

- Social interactions based on peer-to-peer communication interfaces, where almost any interaction among two agents can be considered social. This approach is mostly found in Multi-Agent Systems (MAS) research field;
- Social-Network Services (SNS) based approach as a media for social interaction, where "social interaction" refers to the use of Social Networking platforms' architectures to structure human-human, machine-human, or machine-machine data exchanges. Social Networking platforms and services being commonly referring to services such as Facebook or Twitter, due to the vast amount of data they could provide, or more occasionally to specifically developed platforms;
- Human-inspired social relationship based sociability model, where human-inspired social relationships are transposed into technical or socio-technical systems to structure them. For instance, those social relationships can be based on anthropological sociology works such as Fiske's ones [59].

The use of these 3 sociability types to study the literature sample shows a certain unbalance (table 2.4). The majority of the studied literature considers social interactions as simple peer-to-peer communication interfaces either between systems and systems, or between human and system (around 57%). Besides, approximately 26% of the papers, mainly supporting SIoT developments, are considering social interactions as SNS-based approaches. These two approaches are in fact clearly expressing a neat distinction between human and technical systems. Yet, the systemic vision of socio-technical systems implies, as seen before, to consider technical and human systems as a whole, and only in few works are social interaction considered as an extension of human sociological models to technical systems. Several illustration example are provided hereafter.

Table 2.4: Sociability type distribution in the retrieved sample

Sociability type	**References**
Social interactions based on peer-to-peer communication interfaces	[8, 220, 176, 78, 46, 208, 12, 6, 123, 61, 178, 210, 169, 57, 209, 171, 10, 190, 4, 214, 106, 211, 219, 9, 124, 146, 51, 137, 38, 142, 70, 206, 184, 92, 180, 68, 41, 225, 131]
Social-Network Services based approach as a media for social interaction	[216, 40, 160, 101, 205, 174, 115, 104, 215, 81, 79, 218, 157, 63, 166, 31, 105, 37]
Human-inspired social relationship based sociability model	[82, 126, 221]

Social Interactions Based on Peer-to-Peer (P2P) Communication Interfaces
This approach is the most common one, and is mainly found in Multi-Agent Systems (MAS) study field. Is this model, any agent that is able to interact with an other is defined as "*social*", whether it is artefactual or not. The developments that are presented below are mainly aiming to achieve human-system integration by technologically enhancing human physical abilities. Hence, these are defined as "*interconnected systems (computers, cyber physical devices, and people) "talking" to each other across space and time, and allowing other systems, devices, and data streams to connect and disconnect*" [175]. Enunciated to provide a definition for Cyber-Physical Human Systems (CPHS), this definition is equally consistent with technological concepts such as Human-in-The-Loop Cyber-Physical Systems (HiTLCPS) [162], consisting in an embedded system improving the ability of a human being to interact with his physical environment (Fig. 2.9). The "*loop*" being composed of the operator, the embedded system, and the environment. Beyond this very literal approach of HSI, HiTLCPS still provides a physical extension of the human being, via a digital interface.

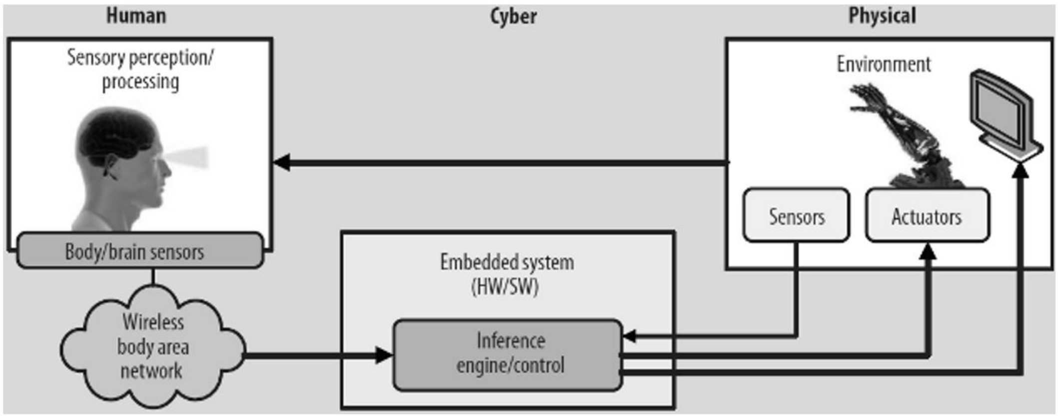


Figure 2.9: Human-in-The-Loop Cyber-Physical Systems (HiTLCPS) [162]

The search for human factor integration is taken further with the development of the "Anthropocentric Cyber-Physical Systems" (ACPS) (Fig. 2.10). It is defined as an architecture "*where the humans are not just interacting with a CPS, but elements of the system affecting its lifetime behaviour*" [146]. The authors present it as an integrated, social, local, irreversible, adaptive, and autonomous system, in line with the continuity of Cyber-Physical Social Systems (SCPS) and Cyber-Physical Social Systems (CPSS). However, unlike previous contributions offering concrete applications, this one remains very conceptual. The most recent development of these approaches until now is the "Social Human-In-The-Loop Cyber-Physical Production System" (Social-HITL-CPPS) [41]. In this approach, the interpretation of human agent's behaviour and its coordination with other agents are identified as the two main challenges for human integration into social (and not just industrial) environments. To meet these challenges, a three-layer architecture is proposed, connecting both human users to the cyber part via user interfaces, and the physical parts (i.e., non-human agents and the environment) to the cyber ones via a network (Fig. 2.11).

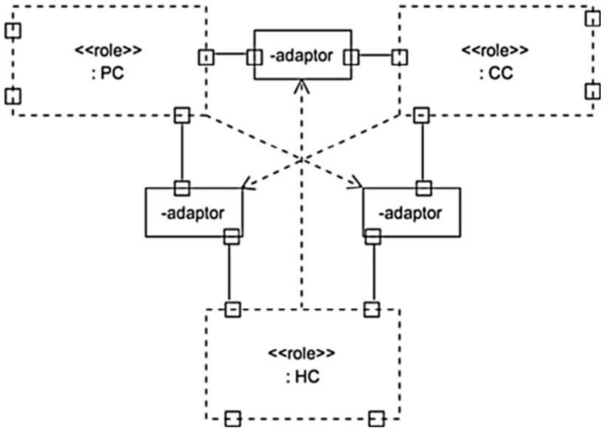


Figure 2.10: ACPS reference architecture [146]

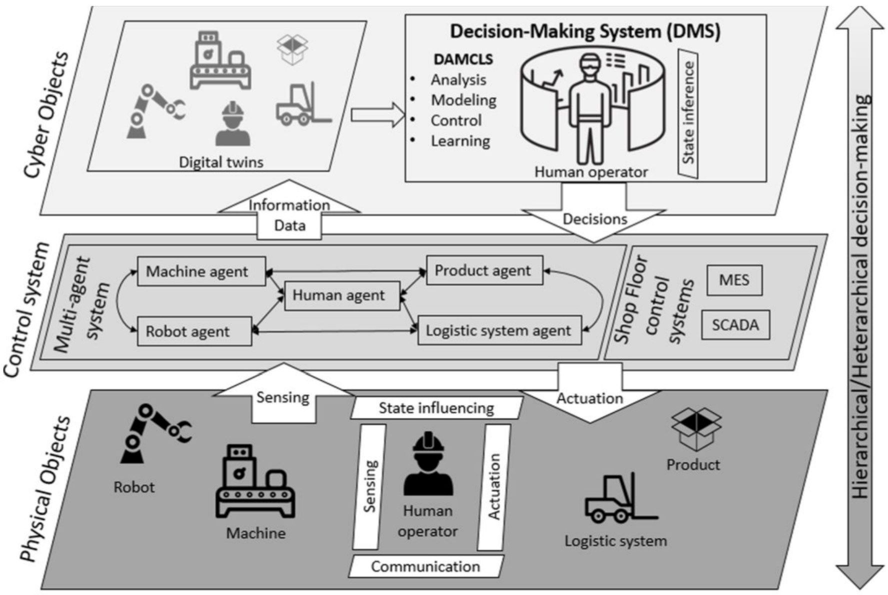


Figure 2.11: Social cyber-physical manufacturing system architecture integrating humans into the loop [41]

Social-Network Services Based Approach as a Media for Social Interaction
This second approach is based on the use "Social Network Services" (SNS) type applications (e.g., Facebook, Twitter, Instagram, etc.) as a media for social interaction between human-human, machine-human or machine-machine. Between 1995 and 2020, a consequent raise of internet users and internet-connected devices has been observed[19] [5]. Nomadic communicating devices (e.g.: laptops, smartphones, and tablets) have become omnipresent in our everyday life. SNS, whose development have been fostered by these devices, have been defined as "*web-based services that allow individuals to (1) construct a public or semi-public profile within a bounded system; (2) articulate a list of other users with whom they share a connection; and (3) view and traverse their list of connections and those made by others within the system*"[26].

First consequence of this raise has been the generation of a huge data among, posing data structuration issues, leading to the idea of using the structures of existing SNS to connect IoT devices into a "Social Web of Things" (SWoT) [69] (Fig. 2.12). The SNS's ability to collect and process data to support the creation or maintenance of social relationships between their users, is there seen as a new way to structure data exchanges within a network of intelligent connected objects (i.e., artefact agents). Today, this idea is fuelling the development of resilient data collection and sharing methods aiming to improve reputation, trust and security between IoT devices (Fig. 2.13) [149, 226]. These methods are based on Graphs, to structure data-connection between devices, Degree distribution to quantify a node's solicitation, and Local Clustering Coefficient to group interlinked nodes as network clusters. Combining these methods to friendship-like relationships ultimately leading to a "social" SNS-based approach.

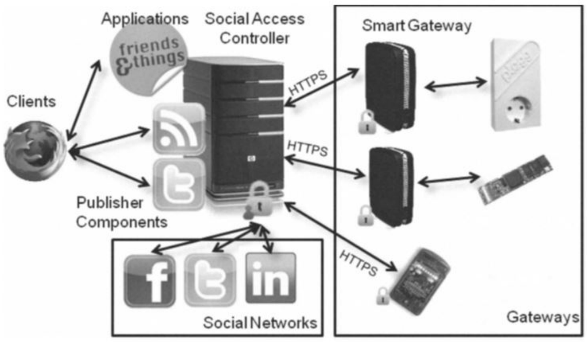


Figure 2.12: Social Web of Things [69]

But Data structuration is not the only use that has been found for SNSs into systems' design. Social networking can equally be used as a way to organise manufacturing systems into distributed Dynamic Resource Communities (DRC) as a "*new cyber-physical-social-connected and service-oriented manufacturing paradigm*" [80]. This Social Manufacturing (SocialM) approach is based on the use of both socialized resources, social media, and social community inspired self-organization for resources (Fig. 2.14). Resource agents (here named Production Service Providers or PSPs) are interacting with each other through a global social relationship network (i.e.: the SNS), enabling them to self-organize into these distributed DRC, aimed to bring resiliency and flexibility to production systems.

[19]Internet World Stats: `https://www.internetworldstats.com/emarketing.htm`

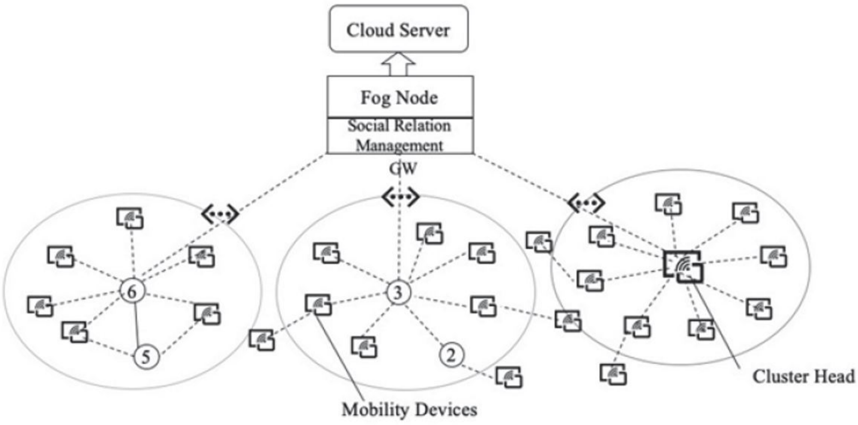


Figure 2.13: Data Collection Model [226]

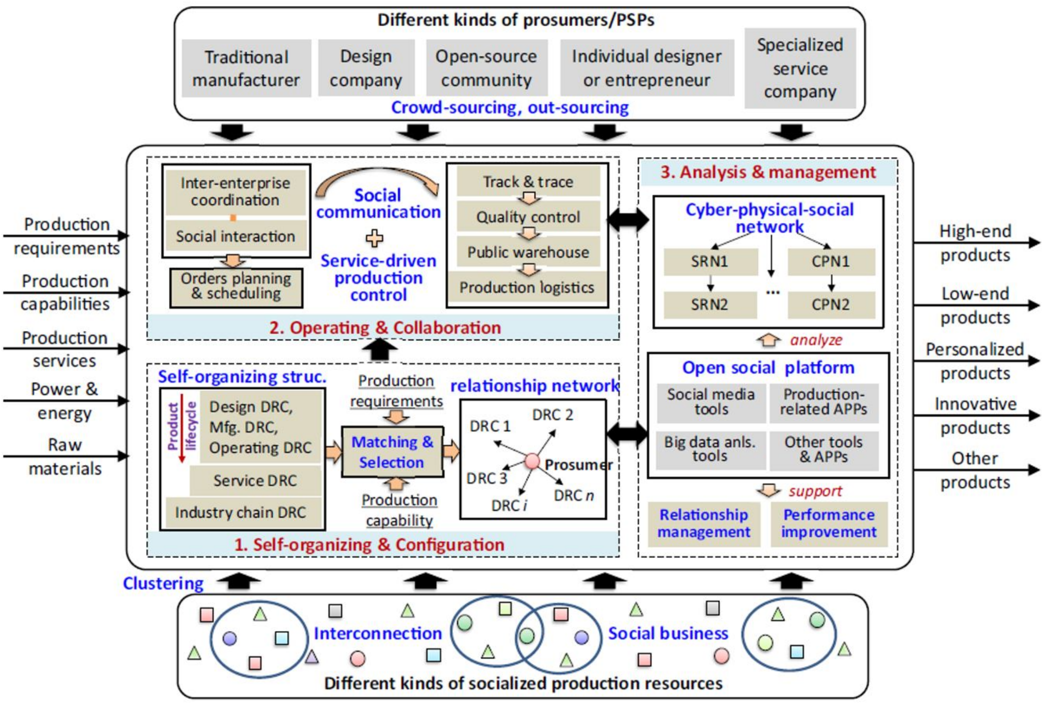


Figure 2.14: Logic framework of SocialM [80]

Human-Inspired Sociability Model: From Social to System Integration
This third approach consists in a transposition of human-inspired social relationships into a technical (e.g., SIoT) or socio-technical system (associating objects and humans). Some years before, the advent of Industry 4.0, a certain lack of consideration for human factors in the field of CPS have been noted [207], and developments were being focused on networked & next-generation embedded systems. Therefore, the proposed the concept of "Cyber Physical Social System" (CPSS) as a "*tightly conjoined, coordinated, and integrated with human and social characteristics*" development of CPS. CPSS being supported by the addition of physiological, psychological, social, and mental spaces to those of cyber and physical spaces (Fig.2.15) [107, 167]. Written as the Word from the Editor for the first issues of the CPSS department of IEEE Intelligent Systems journal, this first approach necessarily stays conceptual. Yet, it has quickly be followed by much more concrete works.

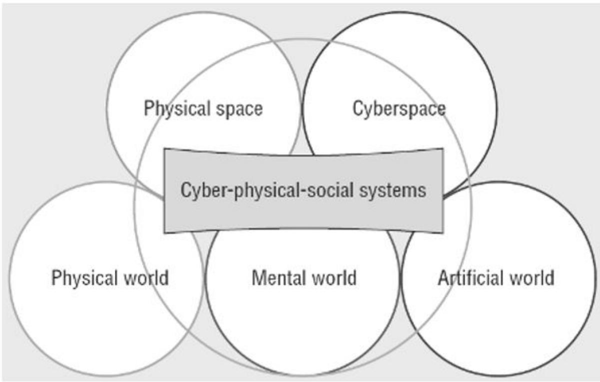


Figure 2.15: From Popper's three worlds to cyber-physical social systems [207]

We can notably cite the "Social Internet of Things" (SIoT) (Fig. 2.16) [14]. Equally based on the identification of the need to structure data into the growing Internet, the goal of this development differs from [69], for it does not focuses on the reuse of existing SNS structures, but rather on the development of a new architecture that would be "*a social network of intelligent objects bounded by social relationships*" [109]. This is based on 5 main social relationships inspired by human systems, such as those developed by [59].

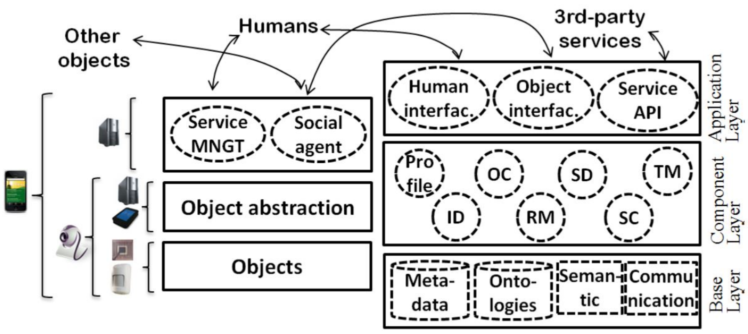


Figure 2.16: Architecture for SIoT: client side (left) and server side (right) [15]

According to Fiske [59], human societies are regulated by four elementary forms of sociability, namely: Communal Sharing (CS), Authority Ranking (AR), Equality Matching (EM), and Market Pricing (MP). This work represents a first attempt to create a typology of social relations, which Atzori and colleagues used as a basis to develop their own typology [15]. They defined the following five inter-object relationships: Parental Object Relationship (POR), Ownership Object Relationship (OOR), Co-Working Object Relationship (C-WOR), Social Object relationship (SOR) and Co-Location Object Relationship (C-LOR). Simultaneously, Atzori and colleagues [14, 15] have developed a support architecture for object-object interactions and the discovery of services and resources within a network of connected objects. Social relationships are established and exploited among objects, but not between their human beneficiaries. Contrasting with previous social approaches, this one relies on human inspired social mechanisms to improve the integration of purely technological systems. However, the relationships expressed in SIoT pave the way for the realization of a paradigm evoked earlier: the "Cyber-Physical Society". It encompasses the definition of Society 5.0 already referred above. It was defined by Shi and Zhuge (Fig. 2.17) as a "Cyber-Physical Socio-Ecosystem" (CPSE) where natural physical space, social space, mental space and cyberspace interact and co-evolve with each other [167]. CPSE deals with the relationships between individuals in a cyber-physical environment and cyber-physical social system. This logic is also found in the work of Pintus and colleagues [145]. These authors define the 'Humanized Internet of Things' (HIoT) as a classic Machine-Machine oriented IoT coupled with SIoT and the "Internet of People" (IoP) [145]. It is easy to perceive, behind this assemblage of paradigms, a larger vision of a socio-technical system of agents, artefacts, and human beings, governed by a set of social relations.

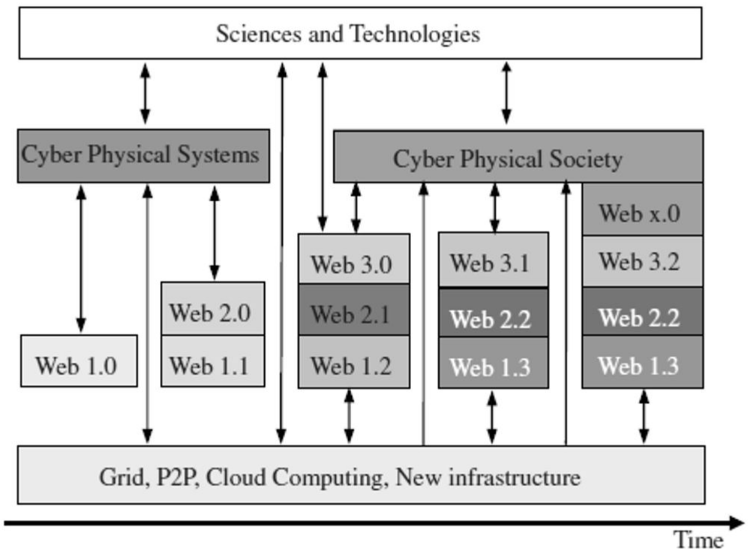


Figure 2.17: Cyber-Physical Society and other systems [167]

Wholeness

Considering the *wholeness* basic concept, it is defined as expressing "*both the interdependence of elements of the system and the coherence of the whole*" [47]. This definition can be associated with the words of Ludwig von Bertalanffy when defining its General System Theory (GST): "*You cannot sum up the behavior of the whole from the isolated parts, and you have to take into account the relations between the various subordinated systems and the systems which are super-ordinated to them in order to understand the behavior of the parts*"[19]. This idea theorizes the emergence phenomenon occurring within complex systems: at the global level are appearing properties that can not be deduced from elementary properties. Wholeness defends the idea that a system is more than the sum of its parts, but also of its interactions with other systems of whatever nature. More particularly, in our context, this concept implies to consider technical and human systems as a whole. To this end, 4 types socio-technical systems, based on these 3 types of sociability can be identified (see figure 2.18). When considering fully technical system, the P2P Communication Interface-based sociability model is supporting *technical systems of communicating objects*. When considering both human and machines, this same sociability model simply supports *technical systems interacting with humans*. A system of communicating objects structured by SNS-based sociology is called a *social network of communicating objects*. Finally, a system of human and cyber-physical agents structured by human-like social relationship (anthropo-social model) is called a *social network of socio-technical agents*. Table 2.5 and figure 2.19 are showing the distribution of our sample regarding this framework. On these elements, it emerges quite clearly that systems are today still not really considered as intrinsically socio-technical ones. Instead of that, it can be stated that the quasi-totality of papers are considering human/social and technical systems as two separate entity. In these papers, contributions are mostly relatives to communication interfaces or mechanics/relationships transposition between one kind of system and another.

Table 2.5: Socio-technical systems distribution in the retrieved sample

System type	References
Technical systems of communicating objects	[171, 173, 51, 174, 8]
Technical systems interacting with humans	[171, 124, 142, 219, 38, 41, 137, 150, 79, 10, 105, 6, 176, 214, 225, 178, 169, 68, 210, 92, 146, 78, 180, 32, 106, 46, 63, 208, 57, 81, 166, 12, 123, 181, 206, 4, 61, 209, 163]
Social networks of communicating objects	[126, 31, 41, 157, 104, 105, 160, 101, 173, 215, 190, 161, 177, 125, 205, 46, 211, 184, 131, 218, 81, 166, 220, 37, 70, 206, 221]
social networks of socio-technical agents	[216, 82]

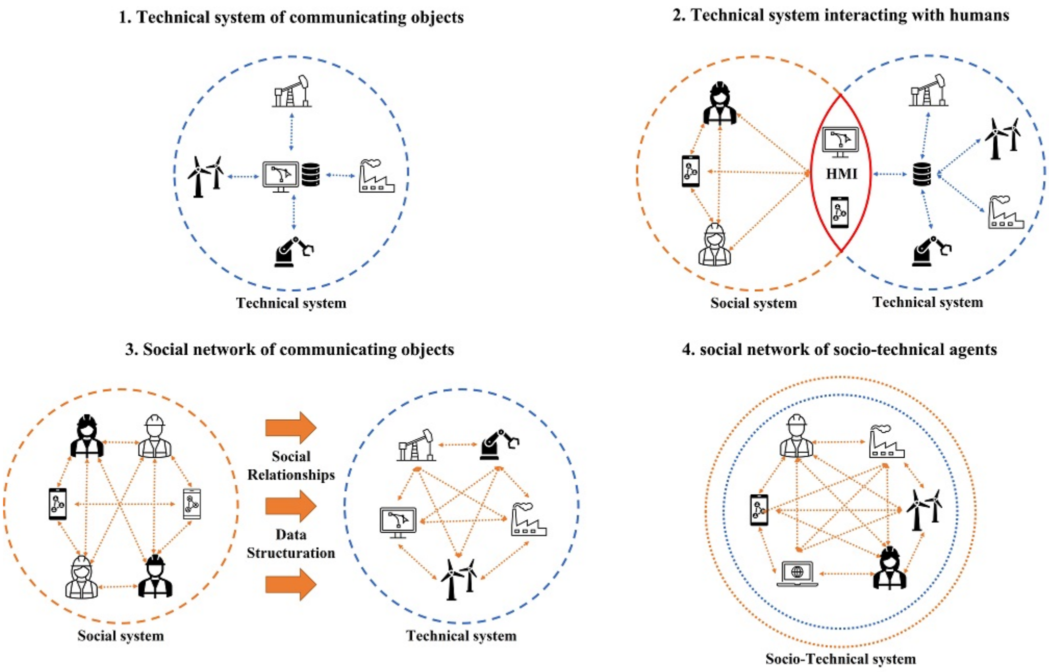


Figure 2.18: The 4 types of social systems

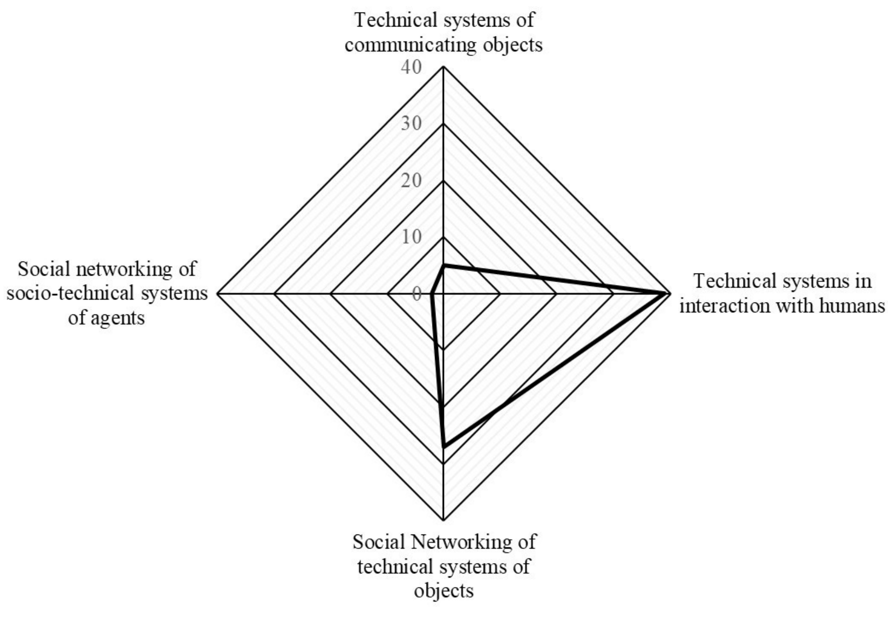


Figure 2.19: Number of publications regarding the system's nature

System/organization

The *system/organization* basic concept can be summarized as focusing on the organization of the constituents of a system as a coherent whole. It can be considered as the very grounding of systemic approach. According to the Systems Engineering Body of Knowledge (SEBoK) [20], the most commonly used definition of a system found science is given by the GST: "*A System is a set of elements in interaction*" [19]. To this broad definition, the works from [102] and [43] added two aspects: first, the system's element are in *dynamic* interaction and second, they are *organized* according to a goal. In the context of systemic approach, this concept will refer to what makes this set of dynamically interacting and goal-pursuing elements a *coherent whole* [47]. This coherence is achieved through the organization of the elements. Here, organization refers to both a structural and a functional aspect i.e.: how is built/arranged the whole, and what this arrangement allows it to do. This arrangement can be done in 2 ways: organization in modules/subsystems, that integrates pre-existing systems as broader systems, and organization in hierarchical levels, new properties are produced and added at each level. In the industrial context, this relates to the notion of control modes and architectures that have been detailed in the 1st chapter. Notably, *system/organization* is expressed by the intrinsic centralized or decentralized nature of the considered (sub)systems (i.e.: hierarchy, heterarchy, isoarchy). This nature can be found at different levels, from the global system's control architecture [146], to the local functioning of a specific subsystem such as resource sharing module [218]. Even if this organizational aspect is not part of the initial search, table 2.6 shows that it is observable into many of the systems exposed in the retrieved papers. Equally, a clear tendency to develop decentralized systems can be noted. This can be simply explained by the very nature of SIoT-based systems, upon which many developments are today conduced.

Table 2.6: Organization type distribution in the retrieved sample

Organization type	References
Hierarchical	[123, 205, 174, 171, 10, 190, 173, 9, 166, 41, 37]
Heterarchical	[8, 220, 176, 78, 46, 160, 101, 171, 215, 214, 146, 81, 206, 218, 157, 63, 41]
Isoarchical	[219, 38]

Complexity

The last basic concept of the systemic approach, *complexity*, refers to the difficulties for analytical and rationalist methods to fully apprehend systems. In a complex system, many components of various nature are interacting with each other, generating emergent and non-linear behaviors, and conferring the system spontaneous ordering characteristics and adaptation abilities. A system's high degree of organization, uncertain or unstable environment, and more globally the impossibility to identify, quantify and master all the elements and relationships at stake are likely to explain these phenomena. Undoubtedly, current and future industrial systems are complex.

[20]SEBoK: `https://www.sebokwiki.org/wiki/Guide_to_the_Systems_Engineering_Body_of_Knowledge_(SEBoK)`

Computerization and the addition of the cyber world to the physical one pushed back the factories' borders, multiplying the number of agents, data, exchanges, etc. tangible or not and overwhelming traditional system synthesis methods [72]. Complexity is the concept that gives full meaning to the development of systemic approaches for, without it, classical analytical methods would have been enough to fully apprehend and master all kind of systems. This complexity has not been studied in detail here. However, the models studied show the dominance of non-analytical approaches, such as MAS or Knowledge Management ones, to deal with it.

2.5.2 Technological Framework analysis

Human-centric solutions & human-machine-interaction

The *Human-centric solutions & human-machine-interaction* pole is presented as aiming to technologically support and enhance human physical and cognitive abilities. To develop the supportive dimension, a first focus has been set on enhancing the system/machines's grasp of different physical or cognitive human factors. To do so, recent research have focused on the development of technologies for human speech, gesture, action and intention recognition & prediction [210, 208, 4, 106, 32, 225] or aiming to track humans' mental or physical strain & stress [216, 40, 4, 181, 137, 79, 68]. On the other hand, to enable the human to get a better grasp of their environment and to better interact with the system/machines, technologies mixing virtual and real worlds have taken a more and more important place. This is the case of Virtual Reality (VR) simulating a virtual and immersive environment with which the user can interact [209], Augmented Reality (AR) superposing in real time virtual elements and information to the real world [163], and Cross or Mixed Reality (MR) going even beyond VR and AR merging physical and cyber worlds to create an interactive cyber-physical hybrid reality, in which humans can evolve [169]. As for the enhancing dimension, focus has been set on both physical and cognitive capabilities. In the retrieved literature, cognitive enhancement is mostly achieved by developing flexible interfaces or technological devices providing relevant data/information to the user, and developing its sensing, learning and decision-making abilities [176, 169, 82, 51, 142]. When saying "physical enhancement", one would immediately think of exoskeletons-type devices and working gears. Yet, safety and physical condition tracking devices [181, 180] are equally part of human physical empowerment as part of industrial systems, along with remotely piloted devices [209]. This last device category calls for the 6^{th} aspect of the pole identified by the European Commission: Human-Robot collaboration, or *Cobotics*, that is receiving considerable attention in the literature [78, 10, 82, 106, 219, 9, 124, 63, 166, 68].

Bio-inspired technologies & smart materials

The *Bio-inspired technologies & smart materials* pole is focusing on the potential applications of bio-inspired technologies and processes into the industrial landscape. According to the European Commission report, those could be integrated with either green properties (Self-healing/repairing, recyclability, re-usability of wastes into raw materials, etc.), or with properties inspired by or adapted to biological systems (living, lightweight and intrinsically traceable materials, embedded biosensors, ergonomic systems). Notably, 3 of these tracks particularly stand out in our sample. The most represented one would concern the development and implementation of embedded- and bio- sensors technologies as key technological components for Human System Integration, by

Table 2.7: Human-centric solutions & human-machine-interaction

Focus	References
Multi-lingual speech and gesture recognition and human intention prediction	[123, 210, 209, 4, 106, 32, 92, 225]
Tracking technologies for mental and physical strain and stress of employees	[216, 40, 4, 124, 181, 137, 79, 92, 68]
Augmented, virtual or mixed reality technologies, for training and inclusiveness	[208, 169, 209, 163, 181]
Enhancing physical human capabilities (Exoskeletons, bio-inspired working gears, and safety equipment	[176, 78, 209, 181, 142, 180]
Enhancing cognitive human capabilities	[176, 178, 169, 190, 82, 106, 51, 142, 206, 41]
Cobotics	[78, 10, 82, 106, 219, 9, 124, 63, 166, 68]

tracking and enhancing human physical & cognitive abilities [46, 4, 79, 92, 166]. Then comes the focus on ergonomics. While sensing technologies can be presented as HSI enablers, ergonomics is their application framework, for it consists in a multidisciplinary research field aiming for human's comfort, safety and productivity increase within its work environment [137]. Better ergonomics being achievable, for instance, through better operator positioning [68], thanks to technologies such as virtual, augmented or cross reality [169], or by better workshop organisation and visual clues [214]. The last property addressed into the studied sample is the self-healing and repairing ability of system's components. This last property is implicitly concerning smart products and materials, such as self-healing polymers [20]. Yet, when considering physical or cyber systems, developing self healing and repairing starts with the development of health, errors and failures detection. To this end, works have been conduced aiming to track industrial assets health as part of a social network of things [160], or to detect and treat time series outliers to ensure data quality [115]. We can assume that the other above-mentioned properties (living, lightweight, intrinsically traceable, recyclable, or re-usable as raw materials) are missing from our research sample for these notions were not aimed at by the search string R.

Real time based digital twins & simulation

The *Real time based digital twins & simulation* pole is focusing on products, processes, systems and systems' components modeling and simulation for optimization, testing or security purposes. One of the greatest challenges in today's industrial systems still lies in their control. Perfectly controlling any system implies in the first place to have a perfect knowledge of it. In the context of complex large-scale industrial systems, only relevant multi-scale models can provide this knowledge. For this reason, many works are today aiming to develop reference meta-models,

Table 2.8: Bio-inspired technologies & smart materials

Focus	References
Self-healing or self-repairing	[160, 115, 10]
Lightweight	/
Recyclable	/
Raw material generation from waste	/
Integration of living materials	/
Embedded sensor technologies and biosensors	[46, 123, 4, 51, 81, 79, 92, 63, 166, 225]
Adaptive / responsive ergonomics and surface properties	[169, 214, 137, 68]
Materials with intrinsic traceability	/

frameworks, and architectures for industrial systems control [216, 208, 211, 150], for analyze and learning purposes [216, 208], or even for trust evaluation [211]. What modeling equally makes possible is the simulation of products and processes that can be used for their optimization [123], or to measure impact of different variables on the system and its environment (physical, social, environmental, etc.) [8, 220, 61, 57, 87]. But maybe the most trendy technology of this pole in current research concerns the development of Digital Twins. Digital Twin consists in a virtual replica of a physical system, product, resource or even human that can be used for design [150], monitoring [12, 210, 184] or optimization [123]. More specifically, in the studied sample, monitoring applications are the ones that are mostly retrieved and are mainly considering HMI and HSI finalities. Yet, systems monitoring aspects equally naturally covers real-time systems modeling, simulation and maintenance issues, for which Digital Twins can be of great use. By integrating physical assets in the cyber space, Digital Twins can be considered as one of the main enabling technologies for CPS development in the context of future industrial systems [146, 166, 221].

Cyber safe data transmission, storage & analysis technologies

The harmonious integration of these new technologies into current already complex industrial systems is one of their major challenges today. A key to achieve integration lies in these technologies' capacity for interoperability with each other, and with pre-existing systems, to form a coherent system of systems. This need for interoperability can be found at every level, whether it concerns structural & organizational aspects (such as enterprise systems' interoperability [174]), or technical and applied ones (such as cyber & physical systems overlapping thanks to visualization interfaces for Cross, Mixed or Enhanced reality [169, 105]).

To enable and support this interoperability, the *Cyber safe data transmission, storage & analysis*

Table 2.9: Real time based digital twins & simulation

Focus	**References**
Digital twins of products and processes	[12, 123, 210, 150, 184]
Virtual simulating and testing of products and processes	[176, 123, 205, 215]
Multi-scale dynamic modelling and simulation	[216, 208, 101, 125, 174, 215, 211, 9, 146, 150, 70, 87, 157, 166, 41, 221, 131]
Simulation and measurement of environmental and social impact	[8, 220, 61, 57, 87]
Cyber-physical systems and digital twins of entire systems	[210, 146, 157, 166, 221, 131]
Planned maintenance	[160, 104, 38]

technologies pole is focusing on the management and securing of the large amount of data that are and will be generated by all the previously enunciated technologies. From their acquisition thanks to sensors technologies or their creation by model-based simulation to their exploitation into real-time and multi-scale models, Digital Twins, etc. data management implies many aspects that already constitute the spine of today's industrial computer systems. Networked, wireless or not, sensors nowadays enable consequent data acquisition and transmission into industrial systems. Notably, last decades' consequent raise of embedded internet-connected devices (smartphones, tablets, laptops, etc.) have seen the emergence of the concept of "Social sensing", where human-related data are directly collected through these nomadic connected devices [46, 79]. After acquisition, data need to be efficiently and safely transmitted, stored, processed and analyzed. The great novelty regarding those tasks lies in fact in the size and complexity of data sets, for which traditional data processing methods and application software prove insufficient. The need to fill this gap fostered the development and use of Artificial Intelligence (AI) technologies and techniques. Notably, Big data management aims to make data usable for further analytic or learning application [92]. This learning aspect has taken a particularly important place in today's research. Current computing capacities coupled to the vast amount of available data have revived the development of neural networks and of machine, deep, and reinforced learning technologies. These can find very concrete industrial applications, for instance through modeling [216, 208], decision making and support [160, 173], human action recognition [209, 32, 225], human-machine interaction [210, 92, 37], or even human behaviors transposition to networked assets [215]. Hence, it can be assessed that data and computer systems' importance is vital for industrial systems. In the context of a globalized and hyper competitive economy, the development of scalable and multi level cyber security takes on its full meaning. Various approaches can be found in literature, from physical identification systems for access and authorization providing [6, 171] to data and assets trustworthiness evaluation [211]. In this search for secure, efficient and interoperable data management, a last aspect was identified: data traceability. If not particularly treated as the main topic of retrieved papers, identification and traceability issues can be retrieve in literature as an underpinning requirement in data management [6, 104, 173].

Table 2.10: Cyber safe data transmission, storage & analysis technologies

Focus	References
Networked sensors	[46, 160, 101, 125, 79, 63, 225]
Data and system interoperability	[101, 169, 174, 31, 105]
Scalable, multi-level cyber security	[78, 6, 171, 124, 126, 63, 68]
Cyber-security/safe cloud IT-infrastructure	[211]
Big data management	[210, 92, 221]
Traceability	[6, 123, 104, 173, 181, 206, 63, 221]
Data processing for learning processes	[216, 208, 123, 160, 210, 209, 173, 215, 32, 92, 37, 225]
Edge computing	[115]

Artificial Intelligence

The *Artificial Intelligence* pole is mainly focusing on advanced data analysis and learning technologies. Advanced data analysis aims to handle and analyze complex, interrelated and dynamic data sets from different origin and scales. Thanks to AI, either causality- or correlation-based relation and network effects within various systems (artefactual or human), can be analyzed and transformed into exploitable data sets for modeling or learning technologies. Yet, while "traditional" correlation-based AI can identify correlation between actions and disturbances in psychomotor work [61] to build predictive experience-based models [161], causality-based AI (or causal AI) goes further. Based on the precise identification of cause and effect relationships between variables, causal AI is focused on the understanding of intrinsic systems' mechanisms. Hence, while correlation-based AI will be able to provide more or less accurate predictions (according to its training model and available data set), causal AI aims to provide reliable decision-making models and tools [165, 36]. Hence, causality based-models have to handle even more complex, yet fundamental, mechanisms. These concepts are underpinning the *Swarm/Distribute* intelligence technologies, aiming to make "clever" behaviors appear from stigmergy among a population of agents structured by simple rules. From a practical standpoint, beyond their analysis abilities, AI technologies are today the subject of great expectations regarding their ability to learn. AI research field covers many learning technologies, the most common ones being usually classified into *Supervised*, *Unsupervised*, and *Reinforcement* learning broad categories [168]. Aside from these 3 categories, Deep learning has today become extremely important in research landscape as a 4^{th} full-fledged approach [215, 106, 37, 225]. Deep learning can be seen as based on Neural Network architectures, able to process the huge amount of data previously mentioned, to reach and even surpass performances of human experts in many domains. Industrial applications of Deep learning would today consists in human-activity recognition for Human-Robot Interaction (see human-centric solutions & human-machine-interaction pole), skills and requirements matching of tasks and operators [106, 38, 184, 37], or to enable systems to autonomously handle unexpected issues (which is one of the main issues regarding automated systems) [161, 38, 184]. Another interest of Deep-learning lies in recent developments of the Artificial Neural Network technologies aiming to reproduce biological (human- or animal-like) neural networks (e.g.: convolutional neural network [210]). These would later contribute for instance to enable/ease individual & human-centric AI [37, 225], or brain-machine interfaces conception.

Table 2.11: Artificial Intelligence

Focus	References
Causality-based and not-only correlation-based AI	/
Show relations and network effects outside of correlations	[216, 125, 211, 126, 70, 92, 225]
Ability to respond to new or unexpected conditions without human support	[161, 38, 184]
Swarm intelligence	/
Brain-machine interfaces	/
Individual, person-centric AI	[37, 225]
Informed deep learning	[210, 215, 106, 37, 225]
Skill matching of human and tasks	[106, 38, 184, 37]
Secure energy-efficiency AI	[215]
Ability to handle and find correlations among complex, interrelated data of different origin and scales in dynamic systems within a system of systems	[61, 210, 161, 38, 225]

Technologies for energy efficiency & trustworthy autonomy

The *Technologies for energy efficiency & trustworthy autonomy* pole is focusing on neutralizing the environmental impact related to all these new technologies' energy consumption. Tomorrows' industrial systems will require huge amount of energy, in a world where the need for a sustainable development has become self evident. According to European Commission [53], focus should be set on renewable energy sources, Hydrogen and Power-to-X technologies, Smart dust and energy autonomous sensors development & integration, and low energy data transmission & data analysis. In the retrieved sample these elements are standing out, even if out of search range at first glance, through Energy Mobility Networks [8], Green/Energy-efficiency IoT [218] and AI [215] or Prosumer Community development [31].

Figure 2.20 summarizes the research interest for each of the 6 axes of the technological enablers for Industry 5.0. It appears that the *Technologies for energy efficiency & trustworthy autonomy* is the least covered aspect, barely reaching 5 papers (7%). Then comes *Artificial Intelligence* and

Table 2.12: Technologies for energy efficiency & trustworthy autonomy

Focus	References
Integration of renewable energy sources	[8, 218]
Support of Hydrogen and Power-to-X technologies	/
Smart dust and energy autonomous sensors	/
Low energy data transmission and data analysis	[4, 219, 218, 31]

Bio-inspired technologies & smart materials axes, covered by respectively 15 (22%) and 17 (25%) papers. *Human-centric solutions & human-machine-interaction*, *Real time based digital twins & simulation*, *Cyber safe data transmission, and storage & analysis technologies* axes are taking particular importance in the literature, being present in more than 30 out of the 68 papers (more than 44%). If it is not surprising to see the human aspect particularly standing out, since it is one of the main aspect of the search R, the fact that Digital Twins and real-time simulations-related technologies are taking an important place in research needs to be pointed out. Those are usually seen as ways to cope with emergent phenomenons within complex systems. Figure 2.20 shows that, what lies beneath Industry 5.0's technological enablers is in fact a search to deal with complex industrial systems, where both humans and industrial assets could be considered as one single socio-technical system.

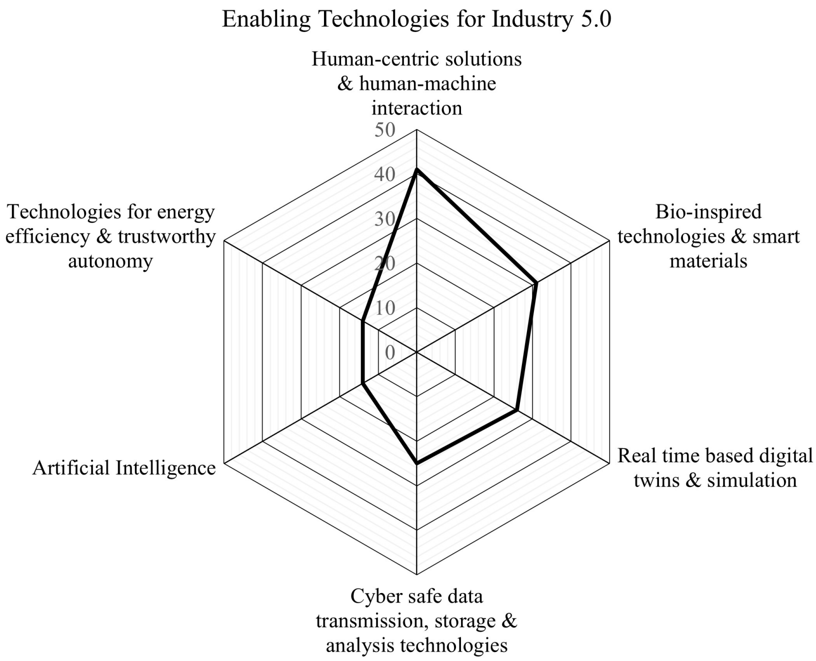


Figure 2.20: Number of publications regarding the technological framework

2.6 Chapter conclusion

In this chapter, a SLR questioning the place given to the human into current and future industrial systems have been conducted. It has shown the great, recent and collaborative international interest for the subject, but equally a certain lack of global vision. The retrieved papers have been analyzed through both a systemic and a technological framework, aiming to tackle a *Technology*, *Organization* and *Human* triptych [30]. The technological framework showed that today's human centric technologies were both support and enabling tools for a better consideration of the human and its variability (related to its physical or cognitive conditions). Notably, the omnipresence of embedded internet-connected devices coupled to the recent progresses of technologies such as new causal AI, explainable AI, Digital Twins, or Augmented/Virtual/Mixed reality, can be seen as a vectors of *tangibility* [27]. Also, the bio-inspired technologies and smart materials, easing human-system inclusion, can be cited as example of promising advances. Those can either be taken as human-machine interaction enhancers, or decision-making supports, guaranteeing human integrity and well-being at work. Hence, these new technologies are not only making the concept of Human-Centered Design credible, but they equally constitute an acceptability vector for future IoT- and CPS-based systems and their developments.

However, new issues and challenges are raised concerning data source management, for instance regarding security and respect for private life, impacting those technologies' social acceptability and their adoption. Before enabling the consideration of future industrial systems as complex socio-technical ones, where both human and industrial assets would be considered as a coherent whole, many gaps will need to be bridged. It will probably take many more years to achieve this. Though, several leads can already be foreseen. From an engineering viewpoint, the raise of HSI as a full-fledged research field carries great potential to better integrate human, thanks to the convergence of both new technologies and multidisciplinary fields (complexity science, organizational theory, cognitive sciences, etc.). Another approach would be to design future systems as human mechatronic societies [196], or based on human societies schemes. This would start by identifying, defining, and formalizing the social relationships occurring within those to apply them to industrial assets [201]. Moreover, papers dealing with societal aspects such as governmental policies or ethics found in the analyzed papers were not developed in this study. This analysis could prove relevant in further works.

Based on the preliminary literature analysis regarding holonic manufacturing architectures and the SLR literature analyses, the following conclusions can be drawn. First, human centricity is now a hot topic in industry based researches. Second, there is a consensus that the complexity of industrial challenges could not be solved by individual technologies, but requires a systemic approach. Moreover, the structuring of any system and the understanding of its functioning is depending on the definition of its components and of the links between them i.e.: holons and their relationships. In literature, those two elements are generally defined, when they are, by abstracting components of a pre-existing system. Consequently, current literature is lacking a generic formal framework for architecture or systems representation and design. Hence, what will be proposed now is a social formal framework resulting for HCA design, including the human operator as one of its holons. This would help answering the two questions enunciated in the introduction. Instead of relying on Human-System interfaces to enable human integration, the idea of using social relationships will rather be exploited to structure the system as a human-like society. This approach echoes the SIoT [14], but aims to extend it to human agents.

Chapter 3

Proposal for social holarchy modelling

3.1 Chapter introduction

A production system is a socio-technical environment, where artefact and human assets are interacting in various ways. Considering the social holonic paradigm, Holonic Control Architectures are composed of holons (assets), social relationships (their interactions), and a control mode (the way holons and relationships are structured). Grounding on the previous literature review, our hypothesis is that a good formalization of social relationships could ease the definition of holarchy between different assets/agents/holons, help defining trust and data-sharing levels, enable localization, coordination or even control between communicating entities. Those might constitute, for instance, ways to solve systems' interoperability and reconfiguration issues in factory based CPS context thanks to machines self-recognition & self-reassignment (see "plugin & produce", from the PERFoRM project [54]). Aside from plugin & produce facilitation, a system structured by human-like social relationships might ease the system's acceptability by the operators and the integration of this last one within the system as one of its agents, and would help to bridge the gap between actual HCA researches and the paradigms pushed by the industry 4.0 [113, 21, 26, 121].

From a holonic point of view, as part of a social HCA, a holon is an entity being either a human or a thing, acting along with other holons constitutive of a system to the realization of its objectives. To achieve those, holons must be able to perceive a part of their environment and to control it by executing specific actions. In manufacturing control, this could either be autonomously achieved by one single holon providing orders to low-level ones (hierarchical structure), might require cooperation between several holons planning their activities together to complete common tasks (heterarchical structure), or a combination of both (hybrid structure) [35]. In literature, the terms "*control architecture*" is commonly used to describe the composition and functionalities of the "*control system*" [164, 83]. The 2^{nd} section will begin by focusing on the composition of the Social HCA: its *components*, its *structure*, its *behaviour*, and its *dynamic*. In its Ph.D thesis, Jimenez provided an extensive work concerning control architectures [83]. Accordingly, this section will rely heavily on this aspect of his work to give initial definitions. Then, section 3 will propose a formal model for holons and relationships definition, that aims to bring genericity to HCA developments. Finally, section 4 will present the framework and software application developed for Social HCA modelling.

3.2 Composition of the HCA

3.2.1 Components

When defining the components of a control system, distinction between *Operational* and *Decision-making* entities is generally made. Operational entities consist in hardware devices subordinated to decision-making ones. Decision-making entities are defined as autonomous communicating subsystems supporting a monitoring activity, problem formulation & solving, and action execution through actuators (i.e. operational entities) [189, 83]. However, this work intends to bring formalism for holonic CPS, with a control approach. For this reason, the components of the system will from now be considered as consistent with the definition of holon that will here be exposed.

The term "holon" has been proposed by Koestler in 1967 as recursive components of self-organizing social and biological systems [91]. In HCA research field, a holon is commonly considered as composed of a combination of both informational and physical processing parts [45]. Consequently, a system's set of holons can both be considered as a sub-system and as a full-fledged holon. For instance, a resource holon could be implemented/developed as a CPS composed by sensors & actuators, and a software holon as a component of the decentralised MES that control them. Hence, the characteristics of holons equally applies to the ecosystem, and reciprocally. To define those characteristics, the implementation aspect of the model had to be kept in mind. For this reason, this work strongly relies on the MAS literature, and notably on the agent models that are commonly used for applications in holonic research.

In their literature review, Chin et al. [39] have admitted an agent to be an autonomous software entity, situated into an environment, monitoring and responding to changes by itself or through communication and collaboration with other agents to achieve goals. Agents being at the same time autonomous, social, reactive and proactive [213]. In this work, a logic-based-like architecture is considered, for the great flexibility and liberty it gives to develop the different components of an agent model. Indeed, those are based upon the symbolic representation and modelling of an agent's behaviour and environment. Concretely, possible internal and external agent/environment states can be represented by sets, while cognitive, measure and application functions are describing the agent functioning itself. Furthermore, the characterization of the holon model is greatly inspired from Ferber's conception, where a MAS is represented as a set of 6 components [58]: an environment "E" where objects "Ob" are located, whose active ones are appointed agents "A". Objects (and thus agents) are related by relationships "R". Agents are able to perform operations "Op" upon the objects, whose applications and consequences on the environment "E" are represented by operators. The holonic focus of our study naturally implies certain divergences from this model. Notably, it is considered that the notion of "holon" includes those of "object" and of "agent". No further consideration is hence brought to the "active" or "inactive" aspect of those.

To get a better grasp of the impact of relationships' nature upon the HCA system, the control theory field is used. In closed-loop controlled systems, outputs are controlled to measure the effects of internal or external disturbances, and feedback are re-injected to correct inputs at each time. This enables to visualize the evolution of the system concerning social relationships establishment and impact. Hence, the autonomous aspect of the holon is considered as being motivated by its ability to observe both its environment and own state, to reach its objectives by constantly adapting itself, and where outputs are controlling a part of the holon's global environment.

3.2.2 Structure

The structural arrangement of the control architecture refers to the way its components are arranged, depending on the relationships binding them. It is the structuring of decision-making entities by different relations/interactions that makes it possible to define what type of architecture, and therefore what control mode, is faced in a system. As seen previously, the decision modes can be classified in 4 classes, from **Class 0** to **Class III** (see figure 1.4) [188]. In this representation, structuring relationships are either hierarchical, or heterarchical. A hierarchical relation between two entities implies the precedence/priority of the decision-making power of one over the other. Contrarily, heterarchical relation between two entities translates their identical decision-making power, without one being hierarchically superior to the other. What is defended in this work is that, more relationships are existing than hierarchical ones. As a matter of facts, in what follows, both hierarchical and heterarchical relationships are the two extreme opposite values of a same *Hierarchical Relationship*. The idea is to bring a social formalism to the definition of control systems and architectures, that would enable the definition of social holarchies based on relationships such as parenthood, ownership, dependency, and of course, hierarchy, either taken individually, or commonly as a whole (fig. 3.1).

The work from Atzori et al. [14] and the idea of structuring the IoT as "*a social network of intelligent objects, bounded by social relationships*" [109], inspired from Fiske's anthropological works [59] is the starting point that inspired the model developed in this work. A.P. Fiske is today commonly recognized as a reference anthropologist specialized in the study of human social relationships. He has notably established that any human society is organized according to 4 elementary forms of sociability, upon which is build the social fabric. Consequently, as a background for this proposal, Atzori's following inter-objects relationships' typology has been preliminary analyzed: *Parental Object Relationship* (POR), *Ownership Object Relationship* (OOR), *Co-Location Object Relationship* (CLOR), *Co-Work Object Relationship* (CWOR), and *Social Object Relationship* (SOR) [14]. While paying a close attention to these, it can be noticed that the 5 relationships established are not based on a same model to link two objects. POR and OOR are established directly among 2 objects, while SOR is conditioned by the pre-existence of an OOR between 2 objects, and then only occurs when the two owners come in touch. This tends to show that relationships can either be *Direct*, established with no intermediaries between two objects, or *Emergent*, established among two objects through the existence of either a third or more objects (Fig. 3.2).

The case of CLOR and CWOR seems a bit particular. In their construction, these two relationships are referring to emergent relationships, indirectly established between two objects. Yet, those are not emerging from relationships that objects maintain with a common third one. Their relationship comes from something they share: a common "location", or a common "work". In our model, those will either be parts of a relationship established among agents that share a part of their data, behaviors, or capabilities, or, accordingly to the nature of the shared "work", to a relationship of hierarchy or dependence. Still, the need to distinguish these two relationships is making sense in the context they were developed within.

The previous statements led to the idea that a social relationships' typology should at first be

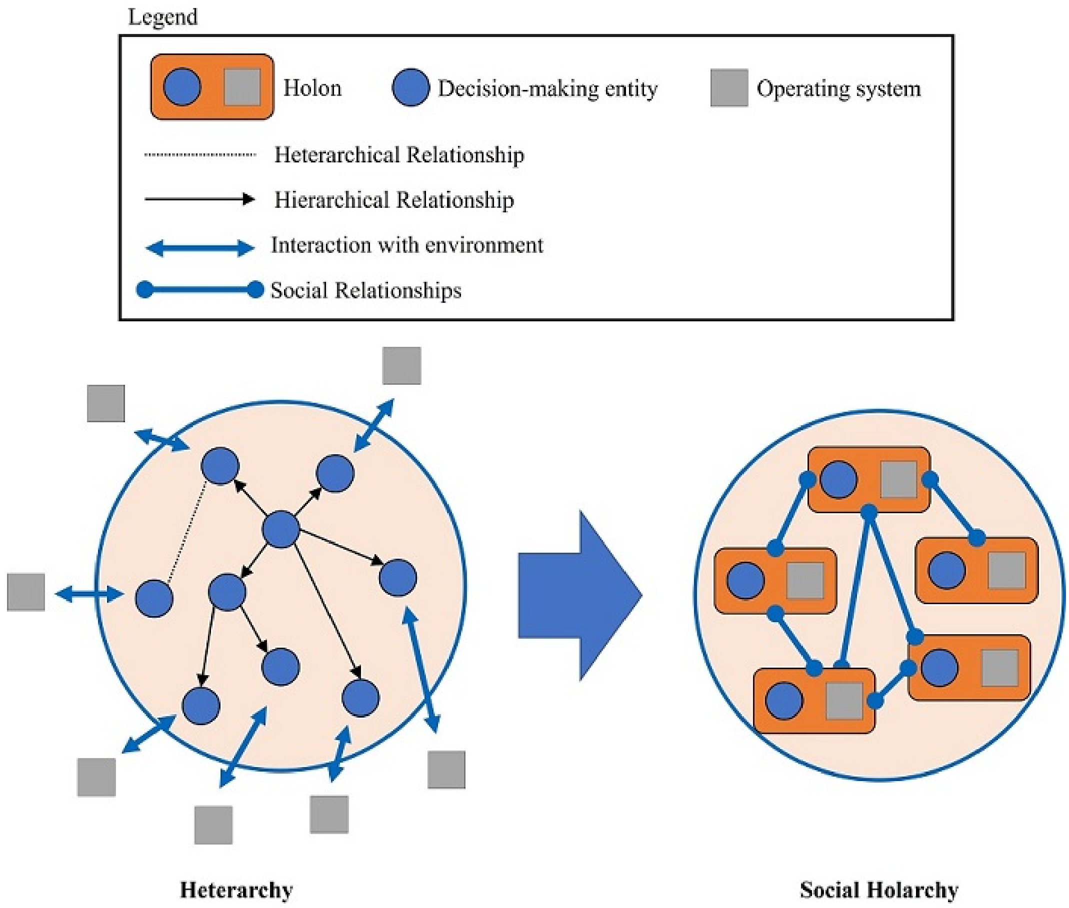


Figure 3.1: Heterarchy (from [83]) vs Social Holarchy's representations for internal view of the control system

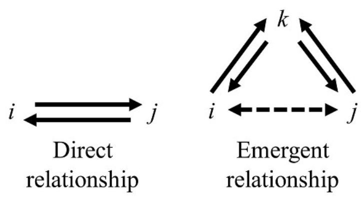


Figure 3.2: *Direct* and *Emergent* relationships between A and B

built upon 4 fundamental *direct* relationships, besides echoing Fiske's 4 elementary forms of sociability. Those being the *Parental*, *Ownership*, *Dependency*, and *Hierarchical* relationships (respectively PR, OR, DR, and HR). Moreover, the existence of "parent", "owner", "dependent", or "superior" holon suggests the existence of related "child", "owned", "required", or "subordinate" ones. Hence, it can be established that direct relationships are presenting an intrinsic duality. If a holon i is in direct relationship with a holon j, then the holon j is in the reciprocal direct relationship with holon i. Consequently, the relationship that holon i has with holon j does not equals the relationship that holon j has with holon i. For instance, considering the Parental Relationship, if a holon i is parent of a holon j, then holon j is child of holon i and holons i and j are in PR. Likewise, *emergent* relationship are defined as resulting from the direct relationships of two holons i and j with a common 3^{rd} one k.

Consequently, a typology can be established, consisting in a total of 4 *direct*, and 16 *emergent* relationships (table 3.1) to which any relationship established among more than 3 holons could be reduced. It must be noted that 4 of the emergent relationships already seems noticeable, for they involve similar direct relationships. Those are the *Co-Parental*, *Co-Ownership*, *Co-Dependency*, and *Co-Hierarchical* relationships (respectively C-PR, C-OR, C-DR and C-HR), and will be the subjects of particular attention in the section 3.3.4.

Table 3.1: Typology of *Emergent* relationships

		$\mathcal{R}^{Direct}_{k\leftrightarrows i}$			
		PR	**OR**	**DR**	**HR**
$\mathcal{R}^{Direct}_{k\leftrightarrows j}$	**PR**	C-PR	POR	PDR	PHR
	OR	OPR	C-OR	ODR	OHR
	DR	DPR	DOR	C-DR	DHR
	HR	HPR	HOR	HDR	C-HR

Relationship degree

Beyond characterizing the existence or not of these relationships, it is equally relevant to quantify them. When defining the SIoT [15], the authors came up with the idea that the degree of interaction among *friend* could be leveraged by establishing a level of trustworthiness, besides studied in later works [128, 127]. In this work, a different view has been preferred, taking as hypothesis that defining a relationship degree among agents of a system might allow to establish relationship activation thresholds, and trustworthiness levels among them.

Three types of relationships degree are proposed in this project. The first one is aimed to quantify direct relationships between two holons i and j. It is noted $\mathcal{D}^{Direct}_{i\longrightarrow j}$ and, just like direct relationships, is oriented. Hence, taking the example of an holon i parent of an holon j, relationship degree will be either noted $\mathcal{D}^{PR}_{i\xrightarrow[PARENT]{}j}$ or $\mathcal{D}^{PR}_{j\xrightarrow[CHILD]{}i}$. This first degree type only involves two agents directly linked, and compare what is shared through the relationship with the intrinsic characteristics of each.

The two other types of relationships degree are concerning the emergent relationships between two holons i and j. Considering the fact emergent relationships are existing at least thought a 3^{rd} holon k, the second degree type, called *Relative*, is established for each of these k, regarding what holons i and j are sharing with it. Noted $\mathcal{D}^{SCR}_{ij,k}$, it represents the strength of the relationship between i and j that is due to k. Yet, i and j could be related by more than one k. For this reason, the third relationship degree focuses on what i and j are sharing, regardless of the holon k their relationship comes from. Hence, this *Absolute* relationship degree is noted $\mathcal{D}^{SCR}_{ij}$. Sections 3.3.5 and 3.3.6 bring a more detailed definition of these relationships.

3.2.3 Behaviour

The *behaviour* (or behavioral functioning) of a control system's component relates to the way decisions are taken by decision-making entities. Overall, decisions are taken by running an algorithm that identify a solution on the basis of sets of *criteria*, *constraints*, and *objectives*. For the most notable methods, this algorithm could consist in protocols (fixed pre-established rules), priority (competitive rules), or heuristics and metaheuristics (optimized rules). Thus, when designing the control system, one or the other of these methods will be chosen depending on criteria such as accuracy, execution time, energy and/or data consumption, etc. Traditionally, these methods are classified as *reactive*, *predictive*, or *predictive-reactive*. To these could be added the *interactive* method, which is a bit particular.

In *reactive* control mode, decision-making components are providing responses to events. Reactive control systems are generally providing fast responses when required, but to the detriment of the responses' optimality. Contrarily, in *predictive* architectures, decision-making components are anticipating events to provide a preventive response. Predictive systems are generally providing optimal or near-optimal solutions, but are time and energy consuming, and detrimental to reactivity. *Predictive-reactive* architectures are hybrid approaches, combining both reactive and predictive ones in various way (although usually sequentially). *Interactive* architectures are not providing responses to event themselves, but are detecting and communicating them to the system's element that is the most likely to provide an answer (often the human operator) [83, 29].

In this study, 3 behaviors will be instantiated, referred as from now *Reactive*, *Consensus*, and *Negotiation* ones. Considering a PDS, running with First-in/First-out (FiFo) decision-making rule, in *Reactive* mode, product holons dynamically reevaluate their own schedule at each nodes or resource, regardless of other holons' situation. *Consensus* brings an additional layer to *Reactive* one: at each node of the system, product holon interrogates its neighbors to detect and solve potential conflicts. The same way, *Negotiation* also overlaps on *Reactive* mode, but holon's interrogation of its neighbors occurs at the level of resource holons, instead of nodes.

3.2.4 Dynamic

Dynamic (or dynamic progression) of a control system usually refers to the motion, actions, and progresses a system performs during its execution to guarantee its "*balancing*". This naturally encompasses the evolution of structure and behaviour of the control architecture, and of the components' interactions. Four stages can be identified: *regulation*, by means of disruption absorption, equalization, or compensation, *functional adaptation*, to cope with changes in the system's environment, *structural adaptation*, to cope with changes in the system's environment, and *structural evolution* to cope with changes in the system's finalities [95, 29]. In this study, the dynamic progression of the social holarchy is intrinsically related to the dynamic establishing of social relationships among holons.

3.3 Formal framework proposal

This section is dedicated to the formal definition and modeling of what has been exposed above. Yet, 2 hypothesis need to be primarily exposed. First, the ecosystem to which the formal model applies is observable, i.e.: all its states can be known, at any moment. Second, if the system is evolving through time, its representation and those of its components is considered at an instant $t \in [0;T]$.

3.3.1 Notation peculiarities

Before going any further, some additional notation subtlety must be clarified. The rules exposed thereafter are taking the case of a holon i for example. Yet, They nonetheless apply to all of the components of the holonic ecosystem that will be exposed afterwards. First, at an instant $t \in [0;T]$, the holon i noted $H_i(t)$ will be composed of a fixed number of sub-holons (i.e. its components) $\{h_{i,n}\}, n \in [\![1; Card(H_i(t))]\!]$. Hence, at the considered instant, uppercase letters are used for the designated component, while lowercase letters are used for its sub-components. Second, if the model is considered at an instant $t \in [0;T]$, with its components at a fixed state, the set of all of a component's possible states is written in calligraphic uppercase: $\mathcal{H}_i$. This writing therefore also corresponds to the component when no consideration is made to the temporal aspect.

Thereby, equations 3.1, 3.2, and 3.3 are expressing what follows. **Calligraphic uppercase without subscript** are referring to the set of all of an element's type, at all time. For instance, $\mathcal{H}$ is the set of all of the system's holons. **Calligraphic uppercase with subscript** are referring to one precise element considering all its possible states i.e., as an element in its entirety. For instance, $\mathcal{H}_i$ is the set of all of the holon i's states. **Non-calligraphic uppercase with subscript**, for instance $H_i(t)$, are referring to a precise element at the instant $t \in [0;T]$. **Non-calligraphic lowercase with subscript** are referring to the set of sub-components $\{h_{i,n}\}$ of a precise element at the instant $t \in [0;T]$.

$$\mathcal{H} = \{\mathcal{H}_i\} \tag{3.1}$$
$$\mathcal{H}_i = \{H_i(t)\} \tag{3.2}$$
$$H_i(t) = \{h_{i,n}(t)\}_{n \in [\![1; Card(H_i(t))]\!]} \tag{3.3}$$

For convenience, the time variable will be obscured in the rest of the document, and notation H_i will be preferred to $H_i(t)$. Likewise, when referring to a set of sub-components of H_i, the notation $\{h_i\}$ will be used, h_i standing for one sub-component taken individually.

3.3.2 Holon formal model

As it could be seen in the literature section, holonic architectures are commonly articulated around 2 basis elements: holons themselves and inter-holon interactions. In the same way, the Social Holonic Architecture is defined as an ecosystem "$\mathcal{E}$" constituted of a set of social holons "$\mathcal{H}$", situally related by a set of dynamic social relationships "$\mathcal{R}$". It can be established:

$$\mathcal{E} = \{\mathcal{H}; \mathcal{R}\} \tag{3.4}$$

A holon "$\mathcal{H}_i$" is defined as a recursive entity, either physical, cyber, or cyber-physical, that evolves within and interacts with the ecosystem "$\mathcal{E}$". The figure 3.3 provides a control representation of "$\mathcal{H}_i$" at time $t \in [0;T]$, written H_i (see subsection 3.3.1). This representation being fixed, we can assess that it can also be assimilated to the state of holon i at time $t \in [0;T]$. The same way, "E" stands for the state of the ecosystem "$\mathcal{E}$" at time $t \in [0;T]$. In this representation, the presence of the sub-ecosystem $E_i = \{H_i; R_i\}$ aims to illustrates that due to its recursive nature, H_i is not only interacting with the ecosystem (other holons and relationships), but also with itself. Hence, what can be noted from H_i's recursive nature is that, if $H_i \in E_i$, then $E_i \in H_i$.

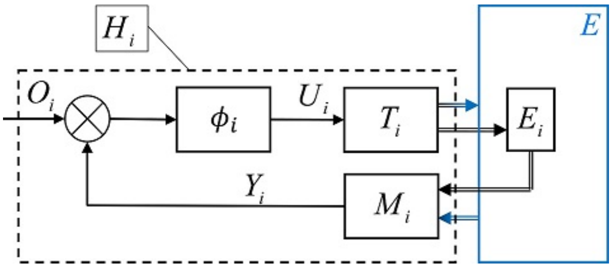


Figure 3.3: Control representation of holon H_i

The functional model of a holon is here inspired from control theory, and more precisely on closed-loop control. Basically, closed-loop control models are composed of both a feedforward and a feedback transfer functions through which pass a serie of signals/inputs/outputs. The functions are assimilated to 3 internal capabilities of H_i, noted "C_i": cognition/decision-making "Φ_i" and transformation "T_i" ones for the feedforward transfer, and measurement "M_i" for the feedback transfer (Eq. 3.7). These capabilities allow H_i to achieve its objective "O_i" within E. The measurement function M_i provides the feedback/perception represented by the output "Y_i" that H_i gets from E and E_i (Eq. 3.8). These feedback are added to the objectives "O_i" to fuel the cognitive function Φ_i (Eq. 3.10) from which come the intentions "U_i" of H_i. The transformation function T_i represents H_i's ability to act on E_i and E accordingly to the input set "U_i" (Eq. 3.9).

Several details must be made about the cognitive function. To effectively reach an objective $o_i \in O_i$, what Φ_i is brought to generate is a process, called ρ_i, defined as a set of k actions $\{a_k\}$ to be performed in order to make the ecosystem evolve from a state to another [213], modelled by the equation 3.5. Yet, if this process is representative of what is necessary to reach the desired state of E, H_i might not be able to achieve some of the planned actions of $\{a_k\}$. This situation is the basis of the Dependency Relationship, which will also be detailed later. Hence, what is called intentions U_i corresponds to the set of actions $\{a_k\}$ that H_i is able to perform i.e., its skills. By extension, $\mathcal{U}_i$ is therefore defined as the set of all actions that H_i is able to perform. These actions are selected by the cognitive/decision-making function "Φ_i" and will lead to the transformation function "T_i".

$$\rho_i \in \mathrm{P}_i = \{a_k\}_{E_{initial} \longrightarrow E_{final}} \tag{3.5}$$

A last element has to be added to this model, although it does not appear on figure 3.3. This element, called Data set "D_i" gathers properties of H_i such as its identification (ID), its type (e.g. product, resource, human ...), its different roles (e.g. planner, transporter, operator...), or its history (previous states, completed objectives, previous values of Y_i, etc.). In the idea, D_i is the element that makes a holon a unique individual. Involved in the cognitive function Φ_i, D_i

is the element that would lead two holons facing a same objective in a given situation, to take different decisions. Hence, from the above, a holon H_i can be represented by:

$$H_i = \{C_i, O_i, U_i, Y_i, E_i, D_i\} \tag{3.6}$$

On this basis, it can be established:

$$\begin{aligned}
\mathcal{C}_i &= \{\Phi_i, \mathcal{T}_i, \mathcal{M}_i\} & (3.7)\\
\mathcal{M}_i &= \{M_i : \mathcal{E} \longrightarrow \mathcal{Y}_i, Y_i = M_i(E_i, \{e\}), \{e\} \subseteq E\} & (3.8)\\
\mathcal{T}_i &= \{T_i : \mathcal{U}_i \longrightarrow \mathcal{E}, (E_i, \{e\}) = T_i(U_i), \{e\} \subseteq E\} & (3.9)\\
\Phi_i &= \{\phi_i : \mathcal{O}_i \times \mathcal{Y}_i \longrightarrow \mathcal{U}_i, U_i = \phi_i(O_i, Y_i)\} & (3.10)
\end{aligned}$$

In the following, either 2 or 3 holons $\mathcal{H}_i$, $\mathcal{H}_j$ & $\mathcal{H}_k$ will be considered, satisfying to the social holon model detailed previously (Eq. 3.6), with at any time $\mathcal{H}_i \neq \mathcal{H}_j \neq \mathcal{H}_k$. In the proposed work, the recursive definition of a holon involves that as soon as one agent is existing, then a system is existing. Hence, any existing holon will necessarily be and be part of a system and will be assumed to be linked to any other holon by at least one social relationship. The next subsection will focus on the definition of the 4 elementary *Direct* social relationships and of a generic model for *Emergent* social relationships. For brevity and convenience, in the next sections, holon notation "$\mathcal{H}_i$" will be replaced by "i". Notably, the couples $(\mathcal{H}_i, \mathcal{H}_j)$, $(\mathcal{H}_i, \mathcal{H}_k)$, and $(\mathcal{H}_j, \mathcal{H}_k)$ will be respectively written (i, j), (i, k), and (j, k).

3.3.3 Direct social relationships formal model

This section brings the formal model of the 4 fundamental direct relationships. Based on the statements made in section 3.2.2, *direct* relationship between i and j, noted $\mathcal{R}^{Direct}_{i \rightleftarrows j}$, will be expressed by:

$$\forall (i, j), \mathcal{R}^{Direct}_{i \rightleftarrows j} \iff (\mathcal{R}^{Direct}_{i \longrightarrow j} \wedge \mathcal{R}^{Direct}_{j \longrightarrow i}) \tag{3.11}$$

To reuse the illustration of the Parental Relationship, if i is parent of j (i.e., $\mathcal{R}^{PR}_{i \xrightarrow[PARENT]{} j}$), then j is child of i (i.e., $\mathcal{R}^{PR}_{j \xrightarrow[CHILD]{} i}$), and i & j are in PR (i.e., $\mathcal{R}^{PR}_{i \rightleftarrows j}$). The 4 direct relationships are individually expressed in what follows.

Parental Relationship: PR

Two holons are in Parental Relationship (PR) when a holon i is parent of another holon j and where the child holon j inherits a set of Data $\{d_{j,i}\} \neq \emptyset$ and/or capabilities $\{c_{j,i}\} \neq \emptyset$ from its parent i. The Figure 3.4 proposes a control representation for Parental Relationship. It can be established:

$$\begin{gathered}
(i, j) \in PR \iff i \text{ is parent of } j \iff j \text{ is child of } i\\
(i, j) \in PR \iff \exists T_i : \mathcal{U}_i \longrightarrow H_j, (\{d_{j,i}\} \subseteq D_j \vee \{c_{j,i}\} \subseteq C_j) = T_i(a_i)
\end{gathered} \tag{3.12}$$

Where $PR \subseteq \mathcal{R}$ is the set of all Parental Relationships. The PR where holon i is parent of holon j being either noted:

$$\mathcal{R}^{PR}_{i \xrightarrow[PARENT]{} j} \text{ or } \mathcal{R}^{PR}_{j \xrightarrow[CHILD]{} i}$$

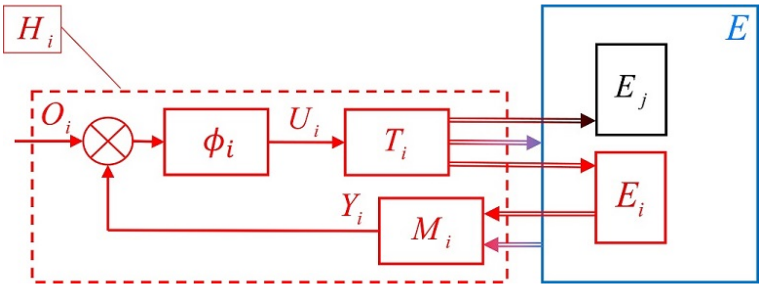


Figure 3.4: A control representation of $(i, j) \in PR$

In a production system, PR relationships would appear when a product receive a distinctive transformation from a specific resource. For example, a drilling machine will be parent of a drilled product.

Ownership Relationship: OR

Two holons are in Ownership Relationship (OR) when a holon i is partially or totally controlling and transforming a part of holon j's ecosystem $\{e_{j,i}\} \subseteq E_j, \{e_{j,i}\} \neq \emptyset$. With the transformation T_i, i influences j's cognitive function Φ_j, while the measurement function M_i enables i to perceive the state of E_j. The Figure 3.5 proposes a control representation for Ownership Relationship. It can be established:

$$\begin{gathered}(i, j) \in OR \iff i \text{ is owner of } j \iff j \text{ is owned by } i \\ (i, j) \in OR \iff \exists T_i : \mathcal{U}_i \longrightarrow \mathcal{E}_j, (\{e_{j,i}\} \subseteq E_j) = T_i(a_i) \\ \text{And } \exists M_i : \mathcal{E}_j \times \mathcal{E}_i \longrightarrow \mathcal{Y}, Y_i = M_i(\{e_{j,i}\})\end{gathered} \tag{3.13}$$

Where $OR \subseteq \mathcal{R}$ is the set of all Ownership Relationships. The OR where holon i is parent of holon j being either noted:

$$\mathcal{R}_i^{OR} \xrightarrow[OWNER]{} j \text{ or } \mathcal{R}_j^{OR} \xrightarrow[OWNED]{} i$$

In a production system, OR relationships would appear when a product enters a resource to be processed. Once the product "loaded" into the resource, resource is physically controlling the product: the resource is then owner of the product.

Dependency Relationship: DR

Two holons are in Dependency Relationship (DR) when a holon j requires an action or a sequence of actions $\{a_{i,j}\} \neq \emptyset$ from a holon i to perform a task it has in its processes but is unable to perform. The Figure 3.6 proposes a control representation for Dependency Relationship. It can be established:

$$\begin{gathered}(i, j) \in DR \iff i \text{ is required by } j \iff j \text{ is dependent on } i \\ (i, j) \in DR \iff \exists \{a_{i,j}\} \in \rho_j, (\{a_{i,j}\} \notin \mathcal{U}_j) \wedge (\{a_{i,j}\} \in \mathcal{U}_i)\end{gathered} \tag{3.14}$$

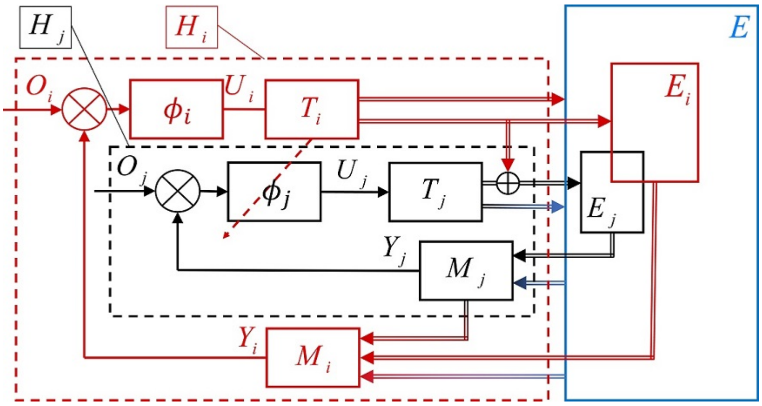


Figure 3.5: A control representation of $(i, j) \in OR$

Where $DR \subseteq \mathcal{R}$ is the set of all Dependency Relationships. The DR where holon i is required by holon j being either noted:

$$\mathcal{R}_i^{DR} \xrightarrow[REQUIRED]{} j \text{ or } \mathcal{R}_j^{DR} \xrightarrow[DEPENDENT]{} i$$

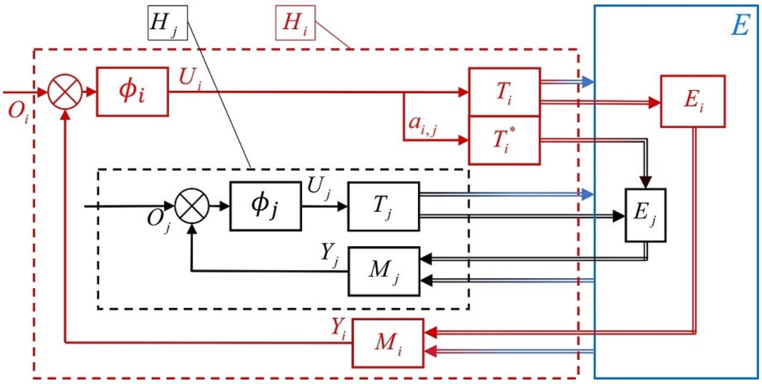


Figure 3.6: A control representation of $(i, j) \in DR$

In a production system, taking the example of a Product-Driven System (PDS) [136], DR relationships would appear when a product needs to be processed by a resource. "Being transformed" is part of the process of the product, but it has no mean to achieve this by itself: the product is then dependent from the resource.

Hierarchical Relationship: HR

Two holons are in Hierarchical Relationship (HR) when a holon i provides a holon j order(s) to transform its environment and reach a desired state. To achieve this, holon j has the possibility to give order(s) to its own subordinates, to act on its environment, or to plan a process. The Figure 3.7 proposes a control representation for Hierarchical Relationship, where an order, or a set of orders $\{o_{j,i}\} \neq \emptyset$ is provided to holon j by an action from holon i, based on holon i's objectives. The completion of this objective is notified to holon i as a feedback, according to holon j's perception M_j. This way, holon j informs its superior of its perception of the objective's competition, which might be inaccurate. It can be established:

$$(i, j) \in HR \iff i \text{ is superior to } j \iff j \text{ is subordinated to } i$$
$$(i, j) \in HR \iff \exists({T_i}^* \in T_i) : \mathcal{U}_i \longrightarrow O_j, \{o_{j,i}\} = {T_i}^*(a_i) \tag{3.15}$$

Where $HR \subseteq \mathcal{R}$ is the set of all Hierarchical Relationships. The HR where holon i is superior holon j being either noted:

$$\mathcal{R}_i^{HR} \xrightarrow[SUPERIOR]{} j \text{ or } \mathcal{R}_j^{HR} \xrightarrow[SUBORDINATED]{} i$$

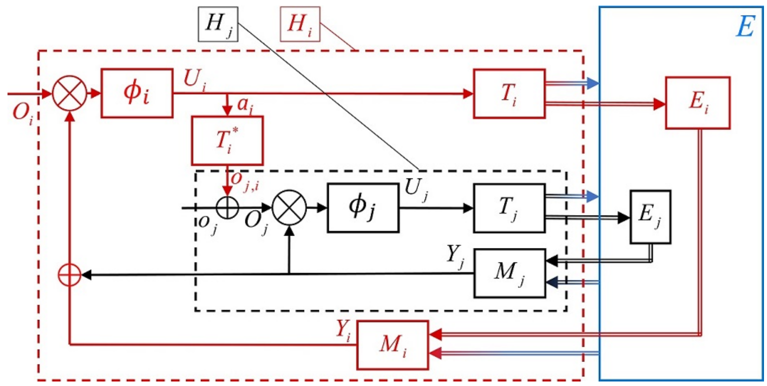


Figure 3.7: A control representation of $(i, j) \in HR$

In a production system, taking the example of a PDS, HR relationships would appear when a product gives the order to the resource to process it. Notwithstanding some constraints (queuing & processing rules, capabilities of the resource, etc.), the product is then the hierarchical superior of the resource in this situation.

3.3.4 Emergent social relationships formal model

This section brings a formal model for the 16 fundamental emergent relationships. Based on the assertions of section 3.2.2, emergent relationship are defined as resulting from the direct relationships of two holons i and j with a common 3rd one k.

Social Contact Relationship: SCR

Emergent relationships are traducing a social contact between 2 holons through a 3rd common one, and can therefore be referred to as *Social Contact Relationships* (SCR), noted $\mathcal{R}^{SCR}_{i \leftrightarrows j}$. Hence, based on equation 3.11 and statements from sections 3.2.2 & 3.3.3, it can be established that any *emergent* relationship between i and j can be expressed by:

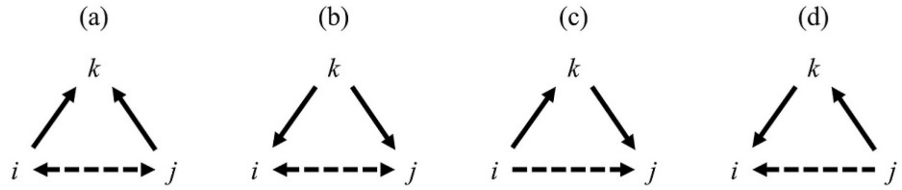
$$\forall(i, j), \mathcal{R}^{SCR}_{i \rightleftarrows j} \iff \exists k, \mathcal{R}^{Direct}_{i \rightleftarrows k} \wedge \mathcal{R}^{Direct}_{j \rightleftarrows k} \tag{3.16}$$

Or otherwise expressed:

$$(i,j) \in SCR \Longleftrightarrow \exists k \in \mathcal{H}, \langle (i,k),(j,k) \rangle \in \mathcal{DR} \tag{3.17}$$

With $\mathcal{DR} \subseteq \mathcal{R}$ is the set of direct social relationships, and where $SCR \subseteq \mathcal{R}$ is the set of all Social Contact Relationships.

This definition of SCR implies 4 cases, detailed and illustrated by figure 3.8. For instance, considering a Parental Relationship between i and k and an Ownership Relationship between j and k. i and j will be related by a relationship $\mathcal{R}^{SCR}_{i\rightleftarrows j}$. This relationship can either express that i is parent of k and j is owner of k (Fig.3.8 (a)), i is child of k and j is owned by k (Fig.3.8 (b)), i is parent of k and j is owned by k (Fig.3.8 (c)), or i is child of k and j is owner of k (Fig.3.8 (d)).



$$\mathcal{R}^{SCR}_{i\rightleftarrows j} \Leftrightarrow \left(\mathcal{R}^{Direct}_{i\to k} \wedge \mathcal{R}^{Direct}_{j\to k}\right) \vee \left(\mathcal{R}^{Direct}_{k\to i} \wedge \mathcal{R}^{Direct}_{k\to j}\right) \vee \left(\mathcal{R}^{Direct}_{i\to k} \wedge \mathcal{R}^{Direct}_{k\to j}\right) \vee \left(\mathcal{R}^{Direct}_{k\to i} \wedge \mathcal{R}^{Direct}_{j\to k}\right)$$

Figure 3.8: *Emergent* relationships configurations

In a production system, it is easy to figure out that these relationships are commons. Yet, except for the 4 "co"-relationships that are expressed below, it is difficult to establish more detailed generalities concerning them. Further developments could nonetheless be considered in future works, to answer specific development's needs, or to formalize noticeable relationships occurring within the system.

Symmetric and Transitive relationships

If *Co-Parental*, *Co-Ownership*, *Co-Dependency*, and *Co-Hierarchical* relationships (respectively C-PR, C-OR, C-DR and C-HR) are meeting the model of the other emergent SCR ones, they presents some specific aspects. The 4 configurations presented by figure 3.8 can be divided in two categories, based on the orientation of the inter-holon relationships:

- Symmetric relationships;
- Transitive relationships.

Symmetric relationships, noted $\mathcal{R}^{SCR}_{i\Longleftrightarrow j}$, are occurring between two holons that are in the same relationship, with the same orientation, with a common third one, as illustrated by figures 3.8 (a) & (b). It can be established that:

$$\forall (i,j), \mathcal{R}^{SCR}_{i\Longleftrightarrow j} \Longleftrightarrow \exists k, (\mathcal{R}^{Direct}_{i\longrightarrow k} \wedge \mathcal{R}^{Direct}_{j\longrightarrow k}) \vee \exists k, (\mathcal{R}^{Direct}_{k\longrightarrow i} \wedge \mathcal{R}^{Direct}_{k\longrightarrow j}) \tag{3.18}$$
$$\text{And } \mathcal{R}^{SCR}_{i\Longleftrightarrow j} = \mathcal{R}^{SCR}_{j\Longleftrightarrow i}$$

For instance, considering symmetric C-PR between i and j, noted $\mathcal{R}^{C-PR}_{i\Longleftrightarrow j}$, if both i and j are children of k, then i and j will be in a same "*Co-child*" relationship with each other. The same goes if both are parents of k.

Transitive relationships, noted $\mathcal{R}^{SCR}_{i\Longrightarrow j}$ are occurring between two holons that are in the same relationship, with the opposite orientation, with a common third one, as illustrated by figures 3.8 (c) & (d). It can be established that:

$$\forall(i,j), \mathcal{R}^{SCR}_{i\Longrightarrow j} \Longleftrightarrow \exists k, (\mathcal{R}^{Direct}_{i\longrightarrow k} \wedge \mathcal{R}^{Direct}_{k\longrightarrow j}) \vee \exists k, (\mathcal{R}^{Direct}_{k\longrightarrow i} \wedge \mathcal{R}^{Direct}_{j\longrightarrow k}) \quad (3.19)$$
$$\text{And } \mathcal{R}^{SCR}_{i\Longrightarrow j} \neq \mathcal{R}^{SCR}_{j\Longrightarrow i}$$

For instance, considering transitive C-PR between i and j, noted $\mathcal{R}^{C-PR}_{i\Longrightarrow j}$, if i is parent of k while j is child of k, then i will equally be parent of j, by transitivity. The same goes with i is child of k while j is parent of k.

Hence, it can be observed that, the case of the 4 co-relationships involving similar direct relationships two distinct models are answered: symmetric and transitive. Concerning the transitive model, the co-relationship between i and j $\mathcal{R}^{SCR}_{i\Longrightarrow j}$ matches the exact same model as direct relationships (even though the relationship is emergent). Then, transitive relationships will for now be associated to *2nd order direct relationships*, answering the model presented in section 3.3.3. Co-relationships will exclusively be associated to the symmetrical model that will be detailed in the 4 next sections.

Co-Parental Relationship: $C - PR$

Two holons are in (symmetric) Co-Parental Agent Relationship ($C - PR$) when they have Data or capabilities in common with a third common holon with which they are in Parental Relationship oriented the same way. It can be established:

$$(i,j) \in C-PR \Longleftrightarrow (j,i) \in C-PR \quad (3.20)$$
$$(i,j) \in C-PR \Longleftrightarrow \exists k \in \mathcal{H}, \langle (i,k),(j,k)\rangle \in PR \wedge \exists \{dc_{ij}\}, \{dc_{ij}\} \neq \emptyset$$

With $\{dc_{ij}\} = (\{d_i\} \cap \{d_j\}) \cup (\{c_i\} \cap \{c_j\})$, where $(\{d_i\} \subseteq D_i, \{d_j\} \subseteq D_j, \{c_i\} \subseteq C_i, \{c_j\} \subseteq C_j) = T_k(a_k)$ and where $C - PR \subseteq \mathcal{R}$ is the set of all Co-Parental Relationships. The $C - PR$ between holon i and holon j being noted:

$$\mathcal{R}^{C-PR}_{i\Longleftrightarrow j} \text{ or } \mathcal{R}^{C-PR}_{j\Longleftrightarrow i}$$

In a production system, C-PR relationships would appear between parallel twin-resources (similar capabilities) or between products from the same production batch (similar data) for example.

Co-Ownership Relationship: $C - OR$

Two holons are in (symmetric) Co-Ownership Relationship ($C - OR$) when they belong to a same owner, with which they are in Ownership Relationship oriented the same way, but none of them owns of the other. It can be established:

$$(i,j) \in C-OR \Longleftrightarrow (j,i) \in C-OR$$
$$(i,j) \in C-OR \Longleftrightarrow \exists k \in \mathcal{H}, \langle (i,k),(j,k)\rangle \in OR \wedge \langle (i,j),(j,i)\rangle \notin OR \quad (3.21)$$

Where $C - OR \subseteq \mathcal{R}$ is the set of all Co-Ownership Relationships. The $C - OR$ between holon i and holon j being noted:

$$\mathcal{R}^{C-OR}_{i \Longleftrightarrow j} \text{ or } \mathcal{R}^{C-OR}_{j \Longleftrightarrow i}$$

In a production system, C-OR relationships would appear between two products on the same conveyor for example.

Co-Dependency Relationship: $C - DR$

Two holons are in (symmetric) Co-Dependency Agent Relationship ($C - PR$) when a third one is able to perform actions both of them have in their processes (common or not) that they are not able to perform, and conversely. It can be established:

$$\begin{aligned} (i, j) \in C - DR &\Longleftrightarrow (j, i) \in C - DR \\ (i, j) \in C - DR &\Longleftrightarrow \exists j \in \mathcal{H}, \langle (i, k), (j, k) \rangle \in DR \end{aligned} \tag{3.22}$$

Where $C - DR \subseteq \mathcal{R}$ is the set of all Co-Dependency Relationships. The $C - DR$ between holon i and holon j being noted:

$$\mathcal{R}^{C-DR}_{i \Longleftrightarrow j} \text{ or } \mathcal{R}^{C-DR}_{j \Longleftrightarrow i}$$

In a production system, C-DR relationships would appear between two products needing to be processed on a same resource for example.

Co-Hierarchical Relationship: $C - HR$

Two holons are in a (symmetric) Co-Hierarchical Relationship ($C - HR$) when they both receive or give at least one order (common or not) from a same third one. It can be established:

$$\begin{aligned} (i, j) \in C - HR &\Longleftrightarrow (j, i) \in C - HR \\ (i, j) \in C - HR &\Longleftrightarrow \exists k \in \mathcal{H}, \langle (i, k), (j, k) \rangle \in HR \end{aligned} \tag{3.23}$$

Where $C - HR \subseteq \mathcal{R}$ is the set of all Co-Hierarchical Relationships. The $C - HR$ between holon i and holon j being noted:

$$\mathcal{R}^{C-HR}_{i \Longleftrightarrow j} \text{ or } \mathcal{R}^{C-HR}_{j \Longleftrightarrow i}$$

In a production system, C-HR relationships would appear between two resources receiving orders from a same product. For instance, in the case of a PDS: a robotic arm processing the product and the conveyor displacing it. Another example would be the case of an ERP providing instructions to two different products.

3.3.5 Direct relationship degree definition

This section brings the definition of the 4 direct relationships' degree as exposed in the subsection 3.2.2.0. These enable the estimation of the strength of a relationship established directly and exclusively between 2 holons i and j, and therefore involve the same characteristics as the relationships between i and j themselves.

PR degree

The parenthood degree of a holon i over a holon j is noted $\mathcal{D}_i^{PR}\xrightarrow[PARENT]{}_j$. It is defined by the ratio between the set of data and capabilities of j that are inherited from i (i.e. $\{dc_{j,i}\}$), and the set of all the data and capabilities of i (i.e. $D_i \cup C_i$). Hence, It can be established:

$$\mathcal{D}_i^{PR}\xrightarrow[PARENT]{}_j = \frac{Card(\{dc_{j,i}\})}{Card(D_i \cup C_i)} \tag{3.24}$$

With $\{dc_{j,i}\} = \{d_{j,i}\} \cup \{c_{j,i}\}$, where $(\{d_{j,i}\} \subseteq D_j \wedge \{c_{j,i}\} \subseteq C_j) = T_i(a_i)$.

Conversely, the childhood degree of a holon j to a holon i is noted $\mathcal{D}_j^{PR}\xrightarrow[CHILD]{}_i$. It is defined by the ratio between the set of data and capabilities of j that are inherited from i (i.e. $\{dc_{j,i}\}$), and the set of all the data and capabilities of j (i.e. $D_j \cup C_j$). Hence, It can be established:

$$\mathcal{D}_j^{PR}\xrightarrow[CHILD]{}_i = \frac{Card(\{dc_{j,i}\})}{Card(D_j \cup C_j)} \tag{3.25}$$

With $\{dc_{j,i}\} = \{d_{j,i}\} \cup \{c_{j,i}\}$, where $(\{d_{j,i}\} \subseteq D_j \wedge \{c_{j,i}\} \subseteq C_j) = T_i(a_i)$.

Note: a holon j can be a strong child of a holon i (i.e. $\mathcal{D}_j^{PR}\xrightarrow[CHILD]{}_i \approx 1$), while this same holon i will only be weakly parent of the holon j (i.e. $\mathcal{D}_i^{PR}\xrightarrow[PARENT]{}_j \approx 0$), and conversely. This would for instance correspond to a situation where a large set of a product's data and capabilities is inherited from its parent, while those only constitute a limited fraction of the parent's ones.

OR degree

The ownership degree of a holon i over a holon j is noted $\mathcal{D}_i^{OR}\xrightarrow[OWNER]{}_j$. It is defined by the ratio between the part of j's ecosystem that is controlled by i (i.e. $\{e_{j,i}\}$), and the ecosystem of i (i.e. E_i). Hence, It can be established:

$$\mathcal{D}_i^{OR}\xrightarrow[OWNER]{}_j = \frac{Card(\{e_{j,i}\})}{Card(E_i)} \tag{3.26}$$

Where $(\{e_{j,i}\} \subseteq E_j) = T_i(a_i)$.

Conversely, the degree a holon j is owned by a holon i is noted $\mathcal{D}_j^{OR}\xrightarrow[OWNED]{}_i$. It is defined by the ratio between the part of j's ecosystem that is controlled by i (i.e. $\{e_{j,i}\}$), and the ecosystem of j (i.e. E_j). Hence, It can be established:

$$\mathcal{D}_j^{OR}\xrightarrow[OWNED]{}_i = \frac{Card(\{e_{j,i}\})}{Card(E_j)} \tag{3.27}$$

Where $(\{e_{j,i}\} \subseteq E_j) = T_i(a_i)$.

Note: a holon j can strongly be owned by a holon i (i.e. $\mathcal{D}_j^{OR}\xrightarrow[OWNED]{}_i \approx 1$), while this same holon i will only be weakly owner of the holon j (i.e. $\mathcal{D}_i^{OR}\xrightarrow[OWNER]{}_j \approx 0$), and conversely. This would for instance correspond to a situation where a great proportion of a product's states are controlled by a resource, that controls many other products simultaneously.

DR degree

The degree a holon i is required by a holon j is noted $\mathcal{D}^{DR}_{i \xrightarrow[REQUIRED]{} j}$. It is defined by the ratio between the set actions (or sequences of actions) from i that required by j to complete its process (i.e. $\{a_{i,j}\}$), and the set of all possible actions (or sequence of actions) of i (i.e. $\mathcal{U}_i$). Hence, It can be established:

$$\mathcal{D}^{DR}_{i \xrightarrow[REQUIRED]{} j} = \frac{Card(\{a_{i,j}\})}{Card(\mathcal{U}_i)} \tag{3.28}$$

Where $(\{a_{i,j}\} \subseteq \rho_i) = T_i(a_i)$.

Conversely, the dependency degree of a holon j to a holon i is noted $\mathcal{D}^{DR}_{j \xrightarrow[DEPENDENT]{} i}$. It is defined by the ratio between the set actions (or sequences of actions) from i that required by j to complete its process (i.e. $\{a_{i,j}\}$), and the process of j (i.e. ρ_j). Hence, It can be established:

$$\mathcal{D}^{DR}_{j \xrightarrow[DEPENDENT]{} i} = \frac{Card(\{a_{i,j}\})}{Card(\rho_j)} \tag{3.29}$$

Where $(\{a_{i,j}\} \subseteq \rho_i) = T_i(a_i)$.

Note: a holon j can be strongly dependent of a holon i (i.e. $\mathcal{D}^{DR}_{j \xrightarrow[OWNED]{} i} \approx 1$), while this same holon j will only represent a weak dependency for the holon i (i.e. $\mathcal{D}^{OR}_{i \xrightarrow[OWNER]{} j} \approx 0$), and conversely. This would for instance correspond to a situation where a resource is essential to the realization of many products.

HR degree

The superiority degree of a holon i over a holon j is noted $\mathcal{D}^{HR}_{i \xrightarrow[SUPERIOR]{} j}$. It is defined by the ratio between the objectives of j resulting from i (i.e. $o_{j,i}$) and the set of all the objectives of i (i.e. O_i). It can be established:

$$\mathcal{D}^{HR}_{i \xrightarrow[SUPERIOR]{} j} = \frac{Card(o_{j,i})}{Card(Oi)} \tag{3.30}$$

Where $(\{o_{j,i}\} \subseteq O_j) = T_i^*(a_i, o_i)$

Conversely, the subordination degree of a holon j to a holon i is noted $\mathcal{D}^{HR}_{j \xrightarrow[SUBORDINATED]{} i}$ It is defined by the ratio between the objectives of j resulting from i (i.e. $o_{j,i}$) and the set of all the objectives of j (i.e. O_j). It can be established:

$$\mathcal{D}^{HR}_{j \xrightarrow[SUBORDINATED]{} i} = \frac{Card(o_{j,i})}{Card(Oj)} \tag{3.31}$$

Where $(\{o_{j,i}\} \subseteq O_j) = T_i^*(a_i, o_i)$

Note: a holon j can be strongly subordinated to a holon i (i.e. $\mathcal{D}^{HR}_{j \xrightarrow[SUBORDINATED]{} i} \approx 1$), while this same holon i will only have a weak superiority upon the holon j (i.e. $\mathcal{D}^{HR}_{i \xrightarrow[SUPERIOR]{} j} \approx 0$) and conversely. This would for instance correspond to a situation where the responsibility perimeter of i largely exceeds the action perimeter of j.

3.3.6 Emergent relationship degree definition

Since section 3.3.4 did not bring detailed formalization for all of the 16 emergent relationship, this section only brings the definition of the 4 remarkable relationships' degree, as exposed in the subsection 3.2.2.0. These enable the estimation of the strength of a relationship indirectly established between 2 holons i and j, through a third one k. Depending on whether it is aimed at representing the relationship between i and j relatively to k, or absolutely between i and j the following *Relative* and *Absolute* degrees are defined.

C-PR degree definition

Relative degree

The relative C-PR degree between 2 holons i and j regarding their respective PR with a common 3^{rd} holon k is expressed by:

$$\mathcal{D}_{ij,k}^{C-PR} = \frac{Card(\{dc_i\} \cap \{dc_j\})}{Card(\{dc_i\} \cup \{dc_j\})} \tag{3.32}$$

With $\{dc_i\} = \{d_{i,k}\} \cup \{c_{i,k}\})$, and $\{dc_j\} = \{d_{j,k}\} \cup \{c_{j,k}\})$;
And where $(\{d_{i,k}\} \subseteq D_i, \{d_{j,k}\} \subseteq D_j, \{c_{i,k}\} \subseteq C_i, \{c_{j,k}\} \subseteq C_j) = T_k(a_k)$.

Absolute degree

The absolute C-PR degree between 2 holons i and j, regardless of their specific relationships with any other holon, is expressed by:

$$\mathcal{D}_{ij}^{C-PR} = \frac{Card((D_i \cap D_j) \cup (C_i \cap C_j))}{Card(D_i \cup D_j \cup C_i \cup C_j)} \tag{3.33}$$

C-OR degree definition

Relative degree

The relative C-OR degree between 2 holons i and j regarding their respective PR with a common 3^{rd} holon k is expressed by:

$$\mathcal{D}_{ij,k}^{C-OR} = \frac{Card(\{e_{i,k}\} \cap \{e_{j,k}\})}{Card\{e_{i,k}\} \cup \{e_{j,k}\})} \tag{3.34}$$

Where $(\{e_{i,k}\} \subseteq E_i, \{e_{j,k}\} \subseteq E_j) = T_k(a_k)$.

Absolute degree

The absolute C-OR degree between 2 holons i and j, regardless of their specific relationships with any other holon, is expressed by:

$$\mathcal{D}_{ij}^{C-OR} = \frac{Card(E_i \cap E_j)}{Card(E_i \cup E_j)} \tag{3.35}$$

C-DR degree definition

Relative degree

The relative C-DR degree between 2 holons i and j regarding their respective PR with a common 3^{rd} holon k is expressed by:

$$\mathcal{D}_{ij,k}^{C-DR} = \frac{Card(\{a_{k,i}\} \cap \{a_{k,j}\})}{Card(\rho_i \cup \rho_j)} \tag{3.36}$$

With $\{a_{k,i}\} \in \rho_i, \{a_{k,i}\} \notin \mathcal{U}_i \wedge \{a_{k,i}\} \in \mathcal{U}_k$;
And $\{a_{k,j}\} \in \rho_j, \{a_{k,j}\} \notin \mathcal{U}_j \wedge \{a_{k,j}\} \in \mathcal{U}_k$.

C-DR absolute degree

The absolute C-DR degree between 2 holons i and j, regardless of their specific relationships with any other holon, is expressed by:

$$\mathcal{D}_{ij}^{C-DR} = \frac{Card(\{a_i\} \cap \{a_j\})}{Card(\mathcal{U}_i \cup \mathcal{U}_j)} \tag{3.37}$$

With $\{a_i\} \in \rho_i, \{a_i\} \notin \mathcal{U}_i$, and $\{a_j\} \in \rho_j, \{a_j\} \notin \mathcal{U}_j$

C-HR degree definition

Relative degree

The relative C-HR degree between 2 holons i and j regarding their respective PR with a common 3^{rd} holon k is expressed by:

$$\mathcal{D}_{ij,k}^{C-HR} = \frac{Card(\{o_{i,k}\} \cap \{o_{j,k}\})}{Card\{o_{i,k}\} \cup \{o_{j,k}\})} \tag{3.38}$$

Where $(\{o_{i,k}\} \subseteq O_i, \{o_{j,k}\} \subseteq O_j) = T_k(a_k)$.

Absolute degree

The absolute C-HR degree between 2 holons i and j, regardless of their specific relationships with any other holon, is expressed by:

$$\mathcal{D}_{ij}^{C-HR} = \frac{Card(O_i \cap O_j)}{Card(O_i \cup O_j)} \tag{3.39}$$

3.4 Modelling framework proposal

This section describes the framework and its software application conceived to ease the modelling of an industrial system's social holonic architecture. Our goal here is to create a model-based software able to monitor a live MAS and to show in real time the social relationships that run through it. This proof-of-concept software will consist in 2 parts: the first one aims at developing modelling tool elements for MAS while the second one aims at developing a MAS-analysis software running upon the models produced by the modelling tool. Here, the instantiating of the notion of "holon" in a MAS pushes us to turn to the notion of agent, which will be used in the following sections.

The following subsections will first detail the mapping of the social holonic architecture formal framework concepts to an UML profile. To do so, the structure of the agents and of the relationships used in the model are detailed. The purpose is to provide enough knowledge to the proof-of-concept software tool concerning the multi-agent application to extract relationships between agents. This will be the subject of the last subsection, where the methods for visualizing and evaluating the social relationships' evolution within the MAS are exposed.

3.4.1 System and Agent‘s structuring

The structure of the MAS can be represented by a class diagram: agent types are modelled by classes upon which "UML stereotype" "agent" is applied. Stereotypes are used to extend UML vocabulary in order to create new model elements with specific properties. Here, the creation and use of this stereotype enable the tool to associate an "agent instance" in the running MAS to an "agent type" in the model (Fig. 3.9). Agent classes are modelled by 2 types of properties: "Data" and "State" (in the model: D_i). We segment the "Data" property into:

- Identification data: any data that enable the agent to identify its informational or physical elements and bind them to him
- Objective data: the objectives set to the agent (e.g. for an agent controlling a product, the product's bill of material)
- Process data: the agent's knowledge concerning environment's physical transformation abilities, their structuring and their request methods (e.g. in the example of a manufacturing application, the machines in the shop-floor associated with the agents that controls them)
- Record data: any kind of data generated during the agent life cycle, where a record of past events is stored

The capabilities of agents are represented by methods, and its behaviors by activities (in the model: C_i). We modelled by activity diagrams the use of the agent's capabilities by a behavior. Capabilities are classified using stereotypes into :

- Decide / Be Decidable
- Transform / Be Transformable
- Measure / Be Measurable

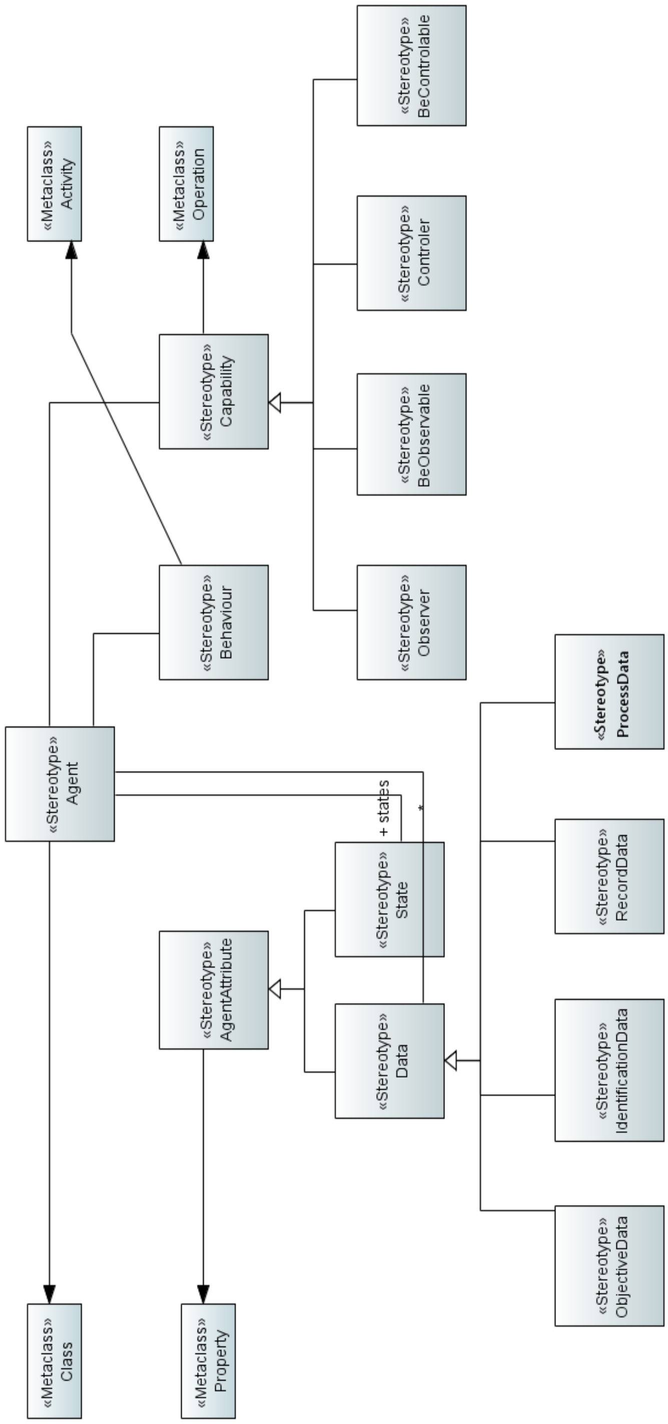


Figure 3.9: Agent's profile diagram

3.4.2 Social relationships modelling

Before establishing relationships among individual agents, we have first defined relationships between agent types. The relationships between agent types can be represented in composite structure diagram: relationships are modelled by “UML collaboration” upon which a stereotype corresponding to the actual relationship’s nature is applied ($PR/HR/DR/OR$, etc.) (Fig.3.11). In this work the elementary direct and emergent relationship previously detailed are modelled.

These generic relationship between agent types are used to set up the *actual* relationships between agent instances. Still, attention have to be paid when instantiating these. For instance, even if the agent types "Product" and "Resource" are related by a generic relationship, a specific product will not automatically be in relationship with every resource agent at all time. Relationships will only occur sometimes, in specific conditions and among specific product and resource agents. A relationship is therefore evolving through “states”. Hence, since relationships might become *active* or *inactive*, we developed the “RelationshipActive” and “RelationshipInactive” states, stereotypes. This switching process is described by a statechart where the “RelationshipActive” and “RelationshipInactive” stereotypes can be applied to states, to show that when entering such states, the relationship status change (Fig.3.11 & 3.10).

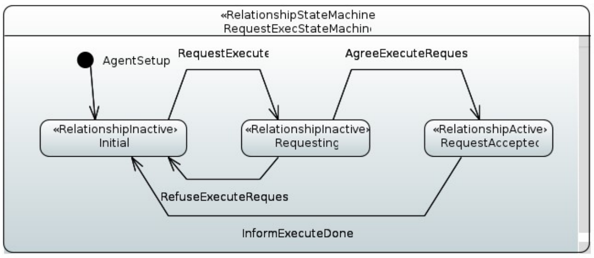


Figure 3.10: Example of relationship activity-triggering State Machine

The transitions between the different states can be associated to events happening in the system. These events’ implementation depends on the actually used MAS. In this proof-of-concept application, the FIPA standard, implemented by the Jade library is used. FIPA, the Foundation for Physical Agent, is an international organization that is dedicated to developing specifications supporting interoperability among agents and agent-based applications. JADE (Java Agent DEvelopment Framework) is a software framework fully implemented in the Java language that complies with the FIPA specification and simplifies the implementation of multi-agent systems through a set of graphical tools that support the debugging and deployment phases. In our case, we used FIPA specifications for implementing the modelling process: events can be matched against the attributes of FIPA’s ACL messages (e.g. performative, protocol, language, etc.), and also against the type of content of the message.

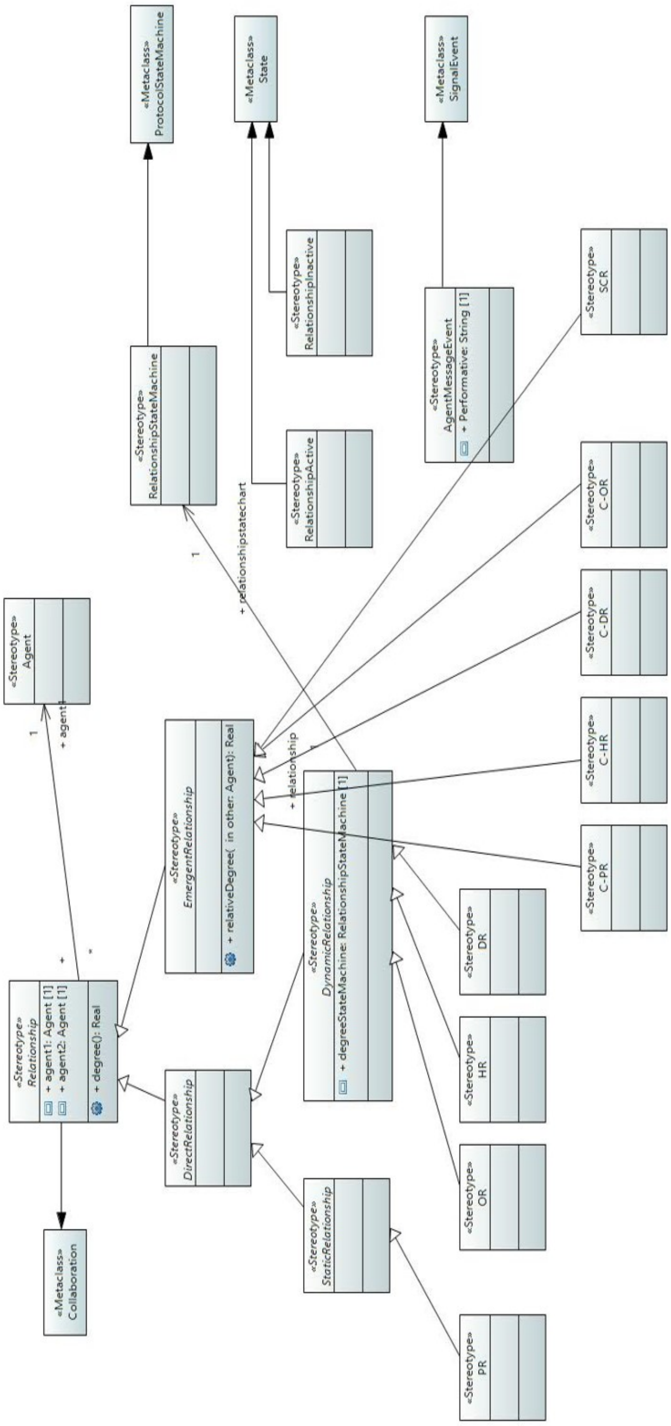


Figure 3.11: Relationship's profile diagram

3.4.3 MAS-analysis software at run-time

Loading the UML model results in a set of objects representing agent types, and a set of "relationship factories [21]" that are used to instantiate the actual relationships between agents. A relationship factory contains the state machine defined in the model, that it instantiates when a new relation is created. Using the same approach as for the "sniffer" tool of the Jade library, we are able to get notification of two kind of events:

- the creation and destruction of agents in the MAS
- the messages exchanged in the MAS between the agents

When a new agent instance appears in the system, the corresponding agent type is searched in the model. If this agent type is related to a relationship (as a source or a target), all corresponding agent instances are retrieved, and for each pair a new relationship is created. When a message is exchanged between agents, all relationships between the agent instances are selected. For each of these, the message is matched against transition filters, making the state machine evolve. When a direct relationship is created, all relationships of the same type with the same target are retrieved to create a co-relationship between the new relationship's source agent and each of pre-existing relationships' source agents.

The content of the system is represented by a multi-graph where each agent instance corresponds to a node, and each active relationship to an edge. The style of the nodes can be set according to the type of agent; likewise, the style of edge reflects the type of relation. The graph is animated according to the stream of messages received. This animated graph is constituting one of the end results of the modelling tool for it enables the real-time visualization and tracking of relationships evolution among agent within an actual MAS.

[21] In an oriented object language, factory is an alternative to constructor, that allows to create objects by instantiating various classes.

3.5 Chapter conclusion

This chapter has proposed a new approach for social hierarchies modelling. This method is based on the formal definition of a human-inspired social (or anthropo-social) relationships' typology, to bring formalism to holonic architectures' structure. This enables the representation any manufacturing system as a society of socially-related holons. First, the reference framework for these social HCA is exposed through the notions of "*components*", "*structure*", "*behaviors*", and "*dynamics*" as the 4 constitutive aspects of HCAs. Notably, the relationships' typology itself is proposed. The second section brings the formal definition & model of these relationships, while the third section is proposing a modelling and visualisation software tool. This tool will be put to contribution in the next chapter to implement the model and establish its proof-of-concept.

Chapter 4

Model instantiation and validation

4.1 Chapter introduction

To support the proposition of the formal model, the technical platform TRACILOGIS[22] from the CRAN will be used as a test-bed system. This platform has a dual purpose. First, it aims to implement, test and compare different traceability techniques (invasive or not) within supply chains in general, and the timber industry in particular. Second, it seeks to provide an environment enabling the implementation of production scenarios, either with a centralized, distributed, or hybrid control context. This cyber-physical technical platform is constituted of an assembly/disassembly cell, upon which are evolving product & resource holons, managed by a control system.

In its basic configuration, the platform operates as a purely reactive Product Driven System (PDS) environment. Yet, previous works have demonstrated the feasibility and relevance of a control method based on consensus, negotiation, or configuration swapping heuristic [29, 118, 119]. Second section is detailing the platform, its components & control modes. Third section presents the instantiation itself, through 3 scenarios implementing different control modes. Fourth section proposes an analysis of social HCA's instantiation, along with a short discussion.

[22]TRACILOGIS: TRACability, Identification and product control for LOGIStics chains, http://www.cran.univ-lorraine.fr/francais/plates_formes/07-tracilogis.php

4.2 Presentation of the test-bed system

This section provides a detailed description of the TRACILOGIS platform, and opens on the 3 scenarios that will be used to support the social holarchy's instantiation. It begins with the presentation of the software architecture, based on MAS development software tools, as it is common usage in the field of holonic search. Then, the different kind of holons, either purely cyber, physical, or cyber-physical, constitutive of the platform, are presented. Last elements to be presented here are the 3 different control modes that are instantiated to support this study.

4.2.1 Description of the software architecture

The software architecture of the TRACILOGIS platform system has been developed using JADE (Java Agent DEvelopment framework[23]). This software platform is used for the development of multi-agent systems and applications, compliant with FIPA[24] standards. It has three basic components: a class library, used to develop the agents, a runtime environment, where agents can evolve, and a set of graphical tools for managing and administering agents. To carry out the proof of concept, the PDS instantiation is performed thanks to a JADE-based platform, grounded on two libraries. The first one, COBALT (COmmon Base for Agent deveLopmenT), is a generic library for the development of software agents. The second one, TOPASE (TracilOgis Platform Agent SystEm), is a specific library to develop control modes for the operating system (Fig. 4.1 & 4.2). Notably, the FIPA Agent Management Specification [60] reference model is used (Fig. 4.3). It provides a normative framework where FIPA agents can exist i.e., be created, registered, located, can communicate, migrates or retires. In this framework, what is called the "Agent Platform" (AP) provides the infrastructure within which agents operate, that is composed of *agents*, *machines*, *operating system*, *agent support software*, and *FIPA agent management components*.

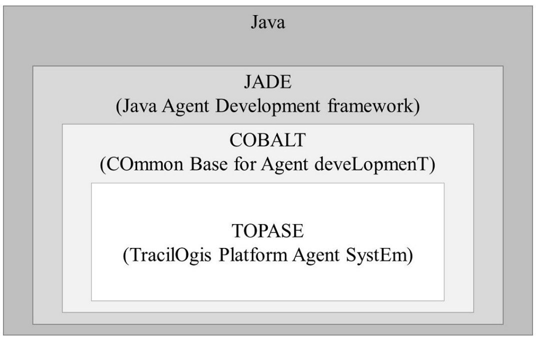


Figure 4.1: Software structure (from [29])

If a large part of this model can be adapted to the needs of specific studies, it still has 2 mandatory component: the "Directory Facilitator" (DF) and the "Agent Management System" (AMS). The DF enables the management of services offered by product and resource holons by declaring those services and finding the holons implementing them. In other words, it has a yellow pages

[23]JADE: `https://jade.tilab.com/`
[24]FIPA: `http://fipa.org/`

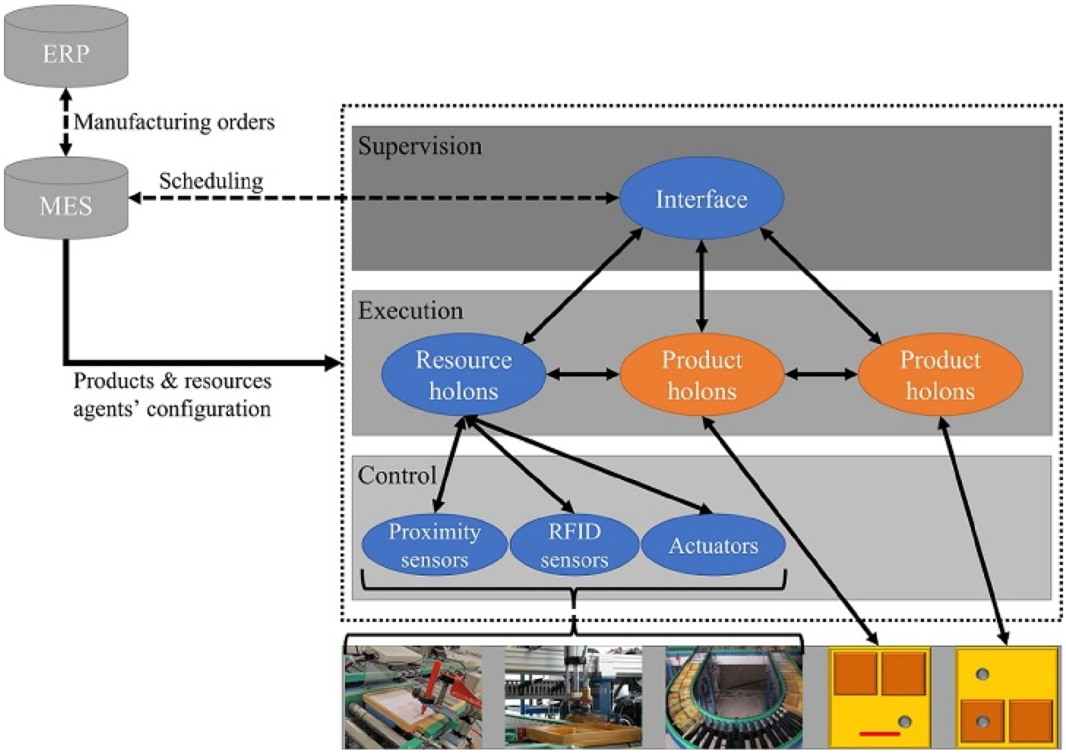


Figure 4.2: TRACILOGIS' control architecture (from [29])

function, where holons are either registering the services they offer, or where they can search out what services are offered by other holons. Concerning the AMS, it provides a white pages services to the system's holons. It is the place where holons register to get an unique identifier. Hence, AMS can exerts supervisory control over access to and use of the system and its components by maintaining a directory of all registered holons. Moreover, for simulation and study needs, 3 additional agents have been developed. The Remote Management Agent (RMA) enables the remote visualization and management of the JADE's technical elements by the human operator. The *Sniffer* Agent is a spectator/spy agent observing and saving the messages exchanged between all holons of the platform. Similarly, the *Database* records each passage of holon produced at the level of an RFID sensor. These two last agents are principally used for traceability purposes. These 3 last components are not part of the FIPA Agent Management Specification.

Overall, these agents are not to be mixed with the platform's holons, for they are related to the system's software architecture, and are then called *Utility agents*. Besides, 3 types of cyber-physical holons are distinguished in the application case: *Interface holons*, *Product holons*, and *Resource holons*. The ERP and the MES presented in Figure 4.2 will not be detailed further, for they operate upstream of the scenario presented below. Indeed, in this study, the ERP/MES components, furnishing the initial production plans, are constitutive of the centralized framework. The decentralized framework that updates these production plans is based on the reactive, consensus, or reactive control modes that will be presented below. Hence, the platform can be seen as constituted of these 4 types of agents and holons, that are presented in the following subsections (Table 4.1). Figure 4.4 additionally provides a representation of the platform's

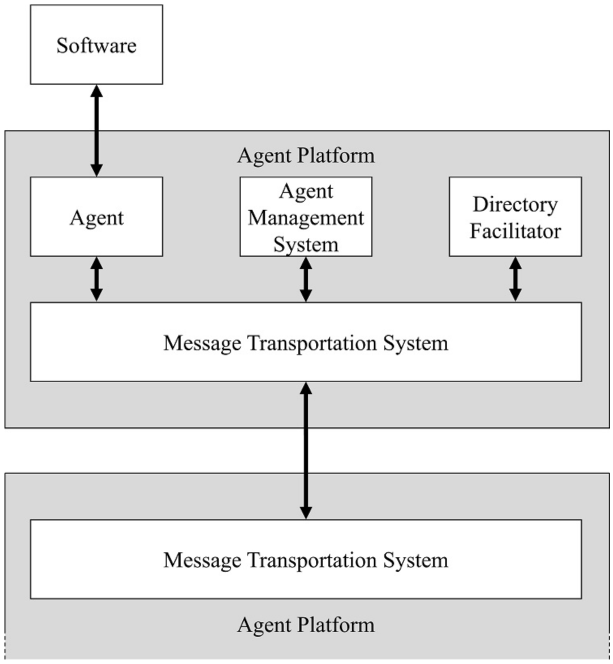


Figure 4.3: Agent Management Reference Model (from [60])

physical layout.

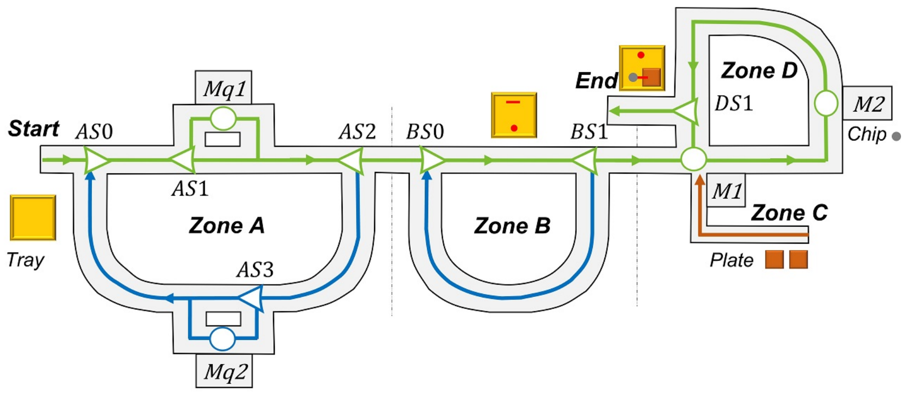


Figure 4.4: Tracilogis platform Layout

4.2.2 Description of interface holons

Interface holons are allowing users, resources, or any other external services, to supervise the system (give orders and receive reports). In terms of holons providing interfaces between the user and the system (physical or virtual), the function is performed by the *ProductLauncher*. It enables the creation of holons' configuration, and their release in the system. Equally, the

Table 4.1: Index for TRACILOGIS' holons and agents

Holon type	**Holon role**	**Holon denomination**
Utility agents	Agent Management System	AMS
	Directory Facilitator	DF
	Collector of inter-holons messages	$SnifferAgent$
	Database entry manager	$Database$
	User interface	RMA
Interface holons	Product creator	$ProductLauncher$
	Emulator of operating system	EMU
Product holons	Tray holons	A^{Tray}
	Plate holons	A^{Plate}
	Chip holons	A^{Chip}
Resource holons	Platform holon	$Platform$
	PLC for Zone A actuators and sensors	$plcA$
	PLC for Zone B actuators and sensors	$plcB$
	PLC for Zone D actuators and sensors	$plcD$
	RFID holon for Zone A	$rfidA$
	RFID holon for Zone B	$rfidB$
	RFID holon for Zone D	$rfidD$
	Zone A shifts	$AS0..3$
	Zone B shifts	$BS0$, $BS1$
	Zone D shift	$DS1$
	Machining station 1	$Mq1$
	Machining station 2	$Mq2$
	Plates assembly station	$M1$
	Chips assembly station	$M2$

EMU holon is an emulator of the physical operating system, used when running simulations before physical instantiation. When running simulations, EMU takes the place of PLC and RFID holons, and can therefore be considered as their equal in this situation.

4.2.3 Description of product holons

Product holons are made out of a combination of assemblies and machining, carried out by machines $Mq1$, $Mq2$, $M1$ and $M2$. The base of all product holon is a wooden tray, equipped with RFID tag, upon which machines $Mq1$ and $Mq2$ will respectively mark red lines or dots, to simulate machining operations, while machines $M1$ and $M2$ will respectively dispose plates and chips in different ways depending of the product holon's configuration. Besides, conveyor and machines M3 and M4 are manually supplied with the trays, plates, and chips. The configuration of a product holon is articulated around the 6 variables presented in the table 4.2 and illustrated by figure 4.5(a). Variables $\tau_n, n = 1, 2$ are referring to the nature of the operations performed by machines $Mq1$ and $Mq2$ on trays, the n index giving here the location of the operation. Variables $\alpha_n, n = 1..4$ are referring to the nature of assembly operations to be carried out by machines $M1$ and $M2$, equally with index n providing the concerned location.

In this study, the state of the tray holon will be related to both its progress in completing its configuration, and its location on the platform, noted p. Hence, the physical state of a tray holon ${A^{\text{Tray}}}_i$ can be written this way:

$$ {X^{\text{Tray}}}_i = (p, \tau_1, \tau_2, \alpha_1, \alpha_2, \alpha_3, \alpha_4) $$

Figures 4.5(b) and (c) are providing two examples of finished tray products. Even if tray holons are considered somehow as the main and most complex product holon, plate and chip holon equally are product ones. These holons only undergoing changes of position, relating to the configuration or to the displacement of the main product holon, their physical state is therefore characterized by their position on the platform and that on the main tray holon. Hence, both plate or chip holon ${A^{\text{Plate/Chip}}}_i$'s configuration can be written this way:

$$ {X^{\text{Plate/Chip}}}_i = (p, \alpha_n) $$

Table 4.2: Tray product holon' configuration variables values and significations

Variable	**Value**	**Signification**
p	$p_{Start}..p_{Exit}$	position
τ_n $n=1,2$	0	no mark
	1	red dot
	2	red line
α_n $n=1..4$	0	no part
	1	plate only
	2	chip only
	3	both plate and chip

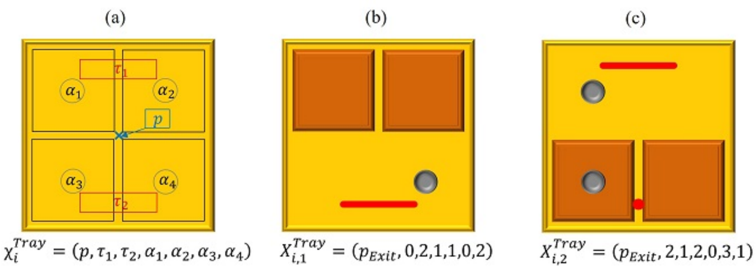


Figure 4.5: Product holon' configurations and states

4.2.4 Description of resource holons

The elements bringing physical transformations to the product ones are called "*Resource holons*". The assembly/disassembly cell is composed of a conveyor system divided into 3 zones, referenced from A, B and D. It is composed of conveyor belts, shifts, machines, presence/proximity sensors, and RFID sensors (Figure 4.6). Zone C consists in a camera-based visual sorting station, attached to the assembly/disassembly cell via the machine M_3 it is supplying. This zone will not be used in the following, for it might disturb the production flow without being particularly relevant in this study. Figure 4.7 provides an overview of the resource holons' physical network, modeled on the physical workflow.

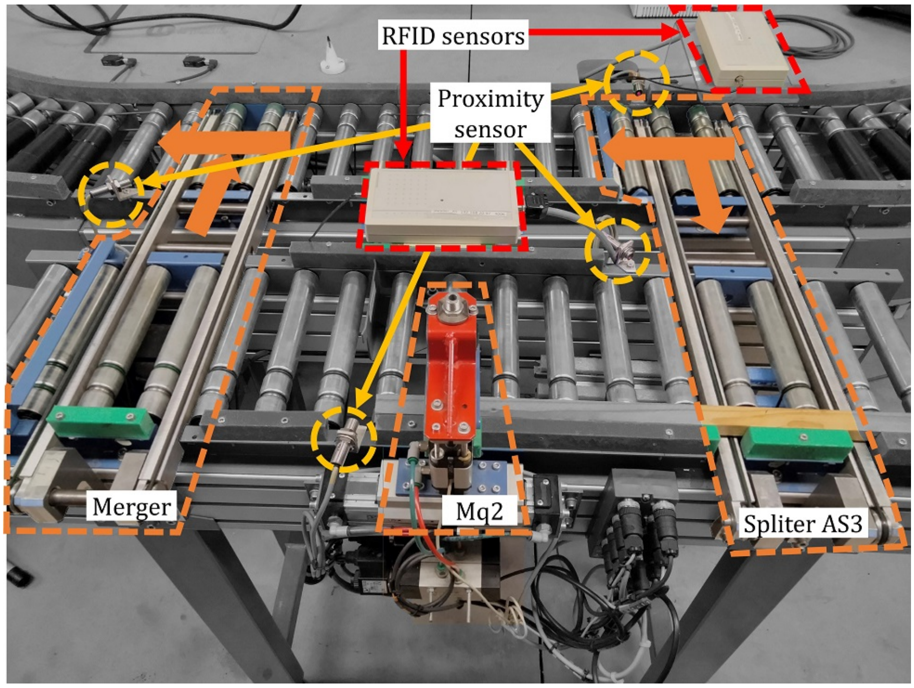


Figure 4.6: $Mq2$ machining area

First of all, it must be noted that each zone is individually managed by an industrial Programmable Logic Controller (PLC), directly linked to the proximity sensors, and in charge of controlling the zone's actuators. These are the *plcA*, *plcB*, and *plcD* holons. The same way, $rfidA$, $rfidB$, and $rfidD$ are managing by zone the network of High Frequency Radio-Frequency IDentification (RFID HF) sensors that are covering the platform. In this study, proximity and RFID sensors will not be considered as resource holons per se, but rather as the physical components of their respective zones' PLC and RFID holons.

The holons providing a change of position (i.e. a coordinate transformation) to product ones are the conveyor belts (Fig. 4.8 (a)). Besides, the holons in charge of product referral at platform intersections are the shift ones, coupled to proximity sensors (Fig. 4.8 (b)). While conveyor belts are continuously active, at constant speed, shift holons are allowing or blocking access through a system of retractable stops. Hence, in order not to complicate the case study too much, conveyor belts will be assimilated to the general "*Platform*" holon even though it could be possible for each

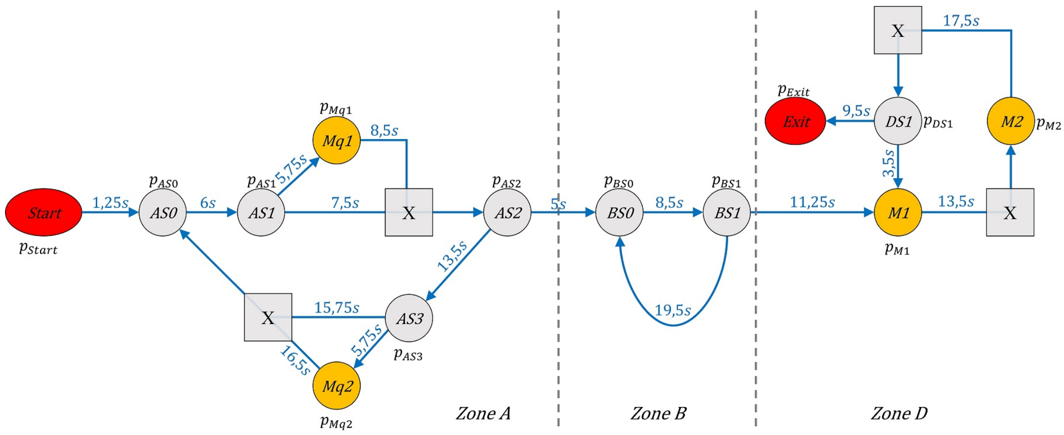


Figure 4.7: Resource holons' network with regard to the platform's workflow

of them to be individually controlled, at variable speed. Equally, even if they factually acting on what is now called the *Platform* holon, shift holons are considered as responsible for product ones' coordinates transformation.

There are 12 shifts on the platform, coupled to proximity sensors, and from two types: splitters and mergers. Due to the configuration on the platform, 2 splitters from zone D are used as angle conveyors, and are therefore included to the *Platform* holon. Historically, only splitters were at first controlled, and thus considered as distinct holons. Mergers were automated to mechanically transfer products holons when detected by proximity sensors. Yet, for the purpose of former studies, 2 of those have been instrumented and are now controllable ($AS0$ and $BS0$ on figure 4.7). A third merger allowing zone D to be looped around itself is considered as part of the machine $M1$, and is therefore not considered as independent shift holon. Therefore, a total of 7 shift holons are present on the platform: $AS0$, $AS1$, $AS2$, $AS3$, $BS0$, $BS1$, and $DS1$. Rectangular element marked with a X-cross on Figure 4.7 are non-controlled shifts considered as part of the "*Platform holon*" along with conveyor sections.

Since the system aims to be representative of an industrial timber industry one, the platform is equipped with 4 machines $Mq1$, $Mq2$, $M1$, and $M2$ simulating operations such as machining, assembly, and disassembly. Machines $Mq1$ and $Mq2$ are dedicated to machining tasks. In the case of TRACILOGIS, both could either mark red lines or dots on the product holons (Fig. 4.8 (c)). Machines $M1$ (Fig. 4.8 (d) & (e)) and $M2$ (Fig. 4.8(f)) are respectively assembling plates and chips on the product holons. As exposed before, $M1$ is equally controlling a shift allowing products to re-enter the zone D.

All the transformations performed by resource holons on product ones, along with processing times, are summarized in the table 4.3.

4.2.5 Description of control modes

As exposed before, the TRACILOGIS platform is controlled in PDS mode. The product holon is defined as the "smarter" holon of the system, while resource ones only have partial perception of

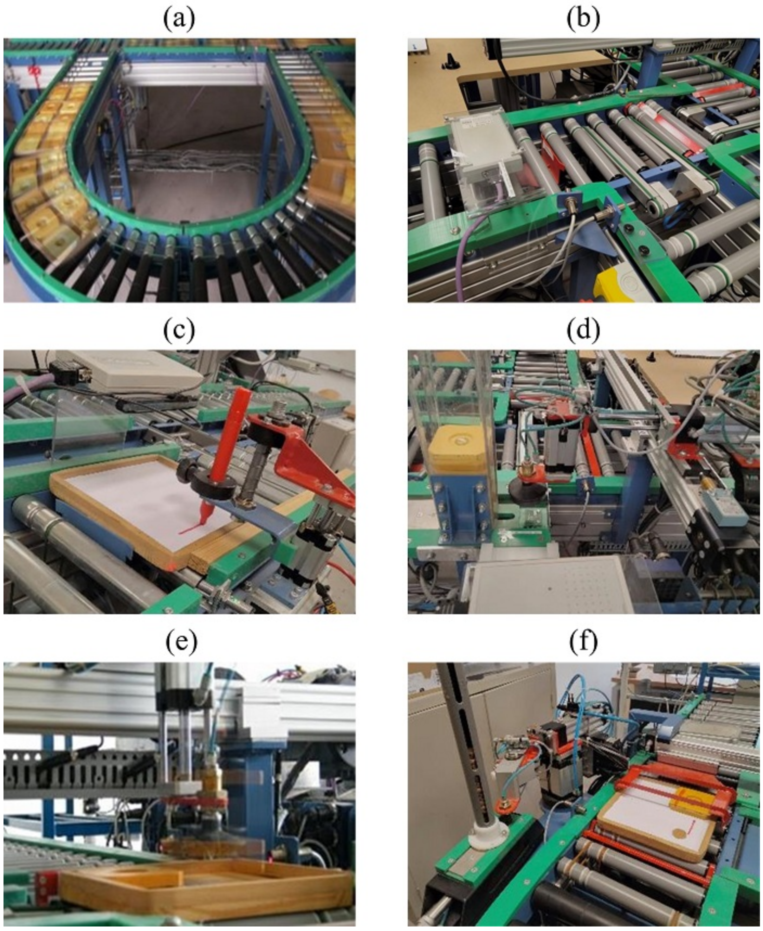


Figure 4.8: Tracilogis' resource holons

their environment. On the one hand, resource holons have the knowledge of the services they offer, their close neighbors and the travel time between them and these latter. On the other hand, product holons have a broader perception of the TRACILOGIS ecosystem (resource and other product holons position for instance), allowing them to built their own trajectory across the platform. Previous research have led to consider different variation of product-driven modes, aiming to improve the system's resilience to unexpected events such a rush orders. These could rely on the self actualization of the product optimal route (Reactive control), the switching of configuration between products (SWAP control), or on the negotiation between holons to evaluate their priority (Consensus and/or Negotiation control). In the case of TRACILOGIS, the decision-making process concerns 3 distinct situation: (1) solving priority issues between product holons at resource level, (2) solving priority issues between product holons at mergers level, and (3) determining whether the product holon will be moved to waiting areas or will head toward next resource at splitters level.

In purely *Reactive* control mode, product holons are re-calculating their optimal route at each resource passing, based on their own state and resource holons' ones. At first, product holons are

Table 4.3: Transformations performed by resource agents

Resource agents	**Action**	**Sate variables evolution**	**Duration (in sec.)**
$Mq1$	d_{Mq1}	$\tau_1 : 0 \longmapsto 1, \tau_1 \in X_i$	1
	l_{Mq1}	$\tau_1 : 0 \longmapsto 2, \tau_1 \in X_i$	2
	s_{Mq1}	$p : p_{Mq1} \longmapsto p_{AS2}, p \in X_i$	8,5
$Mq2$	d_{Mq2}	$\tau_2 : 0 \longmapsto 1, \tau_2 \in X_i$	1
	l_{Mq2}	$\tau_2 : 0 \longmapsto 2, \tau_2 \in X_i$	2
	s_{Mq2}	$p : p_{Mq2} \longmapsto p_{AS0}, p \in X_i$	16,5
$M1$	$\mu_n, n = 1..4$	$\alpha_k : 0 \longmapsto 1, \alpha_n \in X_i$	9,5
	s_{M1}	$p : p_{M1} \longmapsto p_{M2}, p \in X_i$	13,5
$M2$	$\nu_n, n = 1..4$	$\alpha_k : 0 \longmapsto \{2 \vee 3\}, \alpha_n \in X_i$	7,7
	s_{M2}	$p : p_{M2} \longmapsto p_{DS1}, p \in X_i$	17,5
$AS0$	s_{AS0}	$p : p_{AS0} \longmapsto p_{AS1}, p \in X_i$	6
$AS1$	s_{AS1}	$p : p_{AS1} \longmapsto p_{AS2} \vee p_{Mq1}, p \in X_i$	7,5 $\vee$ 5,7
$AS2$	s_{AS2}	$p : p_{AS2} \longmapsto p_{AS3} \vee p_{BS0}, p \in X_i$	13,5 $\vee$ 5
$AS3$	s_{AS3}	$p : p_{AS3} \longmapsto p_{AS0} \vee p_{Mq2}, p \in X_i$	15,75 $\vee$ 5,75
$BS0$	s_{BS0}	$p : p_{BS0} \longmapsto p_{BS1}, p \in X_i$	8,5
$BS1$	s_{BS1}	$p : p_{BS1} \longmapsto p_{BS0} \vee p_{M1}, p \in X_i$	19,5 $\vee$ 11,25
$DS1$	s_{DS1}	$p : p_{DS1} \longmapsto p_{Exit} \vee p_{M1}, p \in X_i$	9,5 $\vee$ 3,5

discovering their environment by building a graph of resources' position and services (see Figure 4.9). Then, each time it faces a resource holon, the product holon recalculates the shortest path to reach its desired configuration by computing a Dijkstra's algorithm, using its historical data, the graph of resources, and its position at time "t". Depending on the occupation of resources on its route, the product can adapt and update its planned completion date. Besides, each time the product holon reaches a resource one (machine or shift) the FiFo rule is applied.

Figure 4.10 presents a sequence diagram of the interactions occurring when a product holon is reaching a resource one in reactive control mode. It shows that the resource holon first receive an event from the operating system gateway agent (proximity sensors), indicating the presence of a product. It queries the rfid gateway to get the product holon's identity, and immediately inform it about his location. Then, when the resource becomes available, it sends a "ReadyToWork" (R2W) message to the product, that proceed to a transformation request, according to its process plan.

The *Consensus* control mode is based on an algorithm using inter-holons interactions, whose computing is triggered for a product holons and its neighbors each time it reaches a shift holon (splitter or merger). The principle is to make product holons converge towards their objective, regarding a common variable translating their state. In this study, the CoMM consensus algorithm is adopted [118, 44]. The state evaluated here to build prioritization reflects the progress of product holons in the completion of their configuration. This evaluation is here based on the ratio

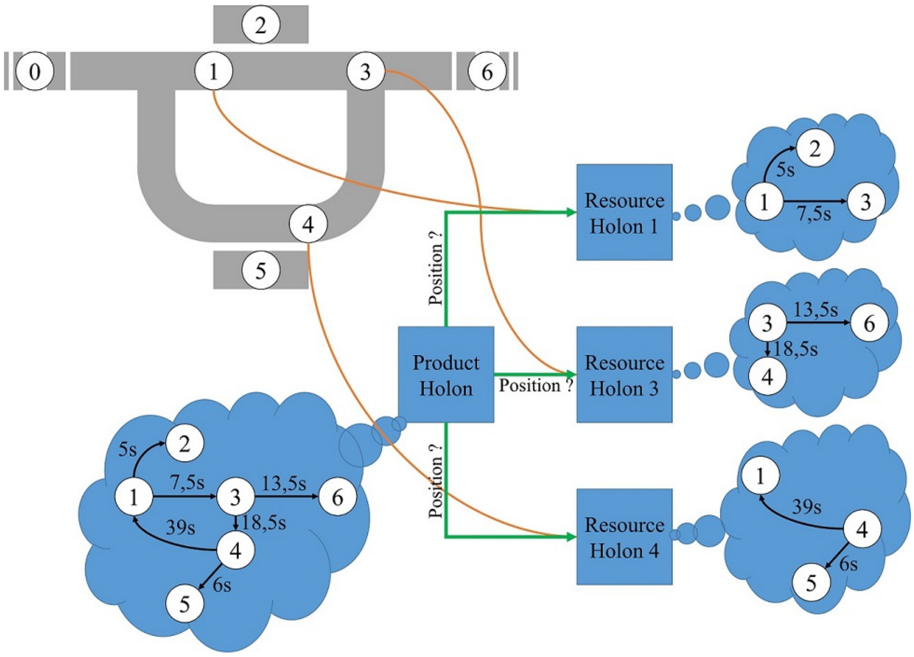


Figure 4.9: Product and resource holons' perception of their environment (from [29])

$r_i = \frac{c_i - {c^*}_i}{d_i - {c_i}^*}$, with d_i product holon i's due date, c_i its estimated completion date, with ${c_i}^*$ its lower bound (regarding its state, its configuration, and processing times). Then, convergence of product holon i's progress and that of its neighbors j, $j \in N_i$, with N_i i's neighbors, is achieved by minimizing the criteria $\sum_{j \in N_i}(r_i - r_j)$. Reevaluating this ratio and minimizing it at each shift passage aims to enable coping with disruption and guaranteeing the system's performance. The notion of "neighborhood" is here defined as the set product holons j that will be located in a certain radius rad around product holon i, at an instant of near future ζ. Hence, a neighbor of product holon i at time t would be noted $N_i(t) = \{j \in \mathcal{H}, d(i,j)(\zeta) < rad, \forall \zeta \in [t, t + \Delta t]\}$.

Figure 4.11 presents a sequence diagram of the interactions occurring when a product holon is reaching a resource one in consensus control mode. At setup time, each product holon subscribes to the intention of other ones. When a product holon subsequently receives an intention, it first determine if the sender product is a neighbor, and if so evaluates its state. When the product holon's location changes, it evaluates its own state to compare it with its neighbors' one. Therefore, when facing mergers, the product holon can decide to let another one go first by canceling its R2W message.

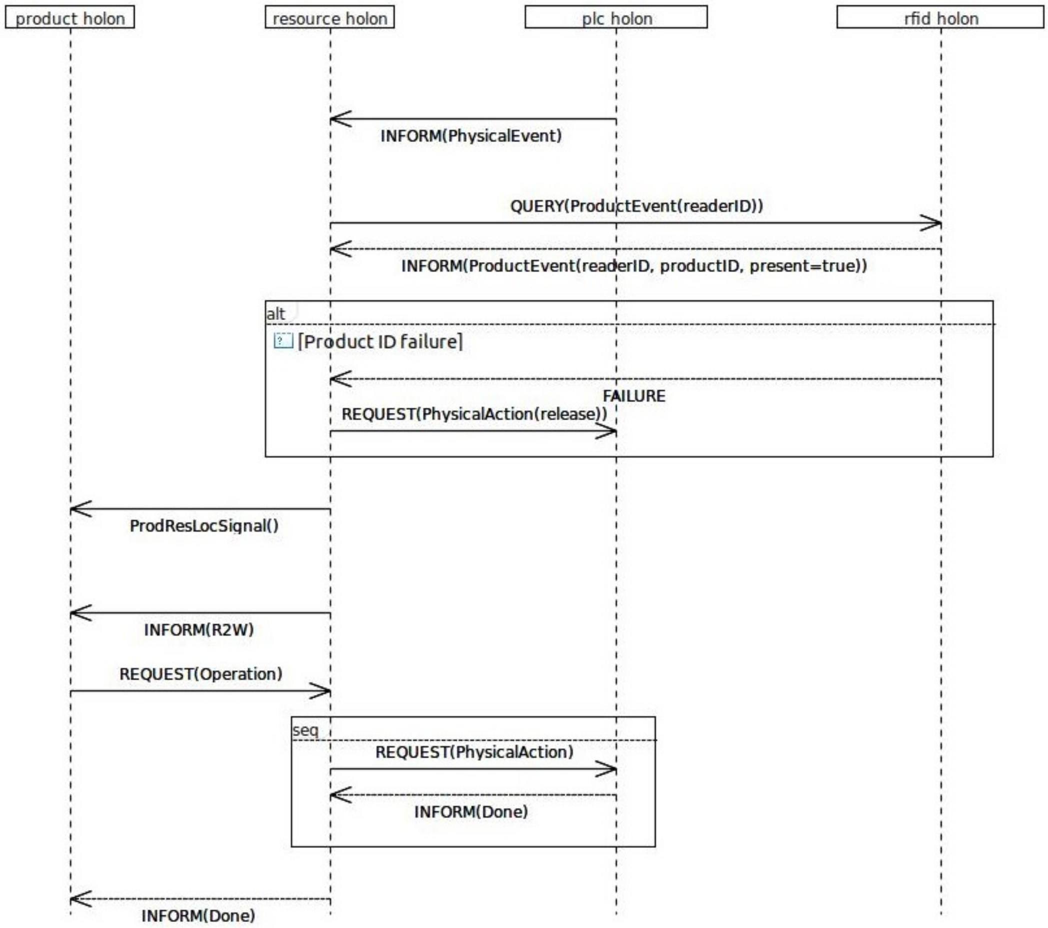


Figure 4.10: Reactive control sequence diagram

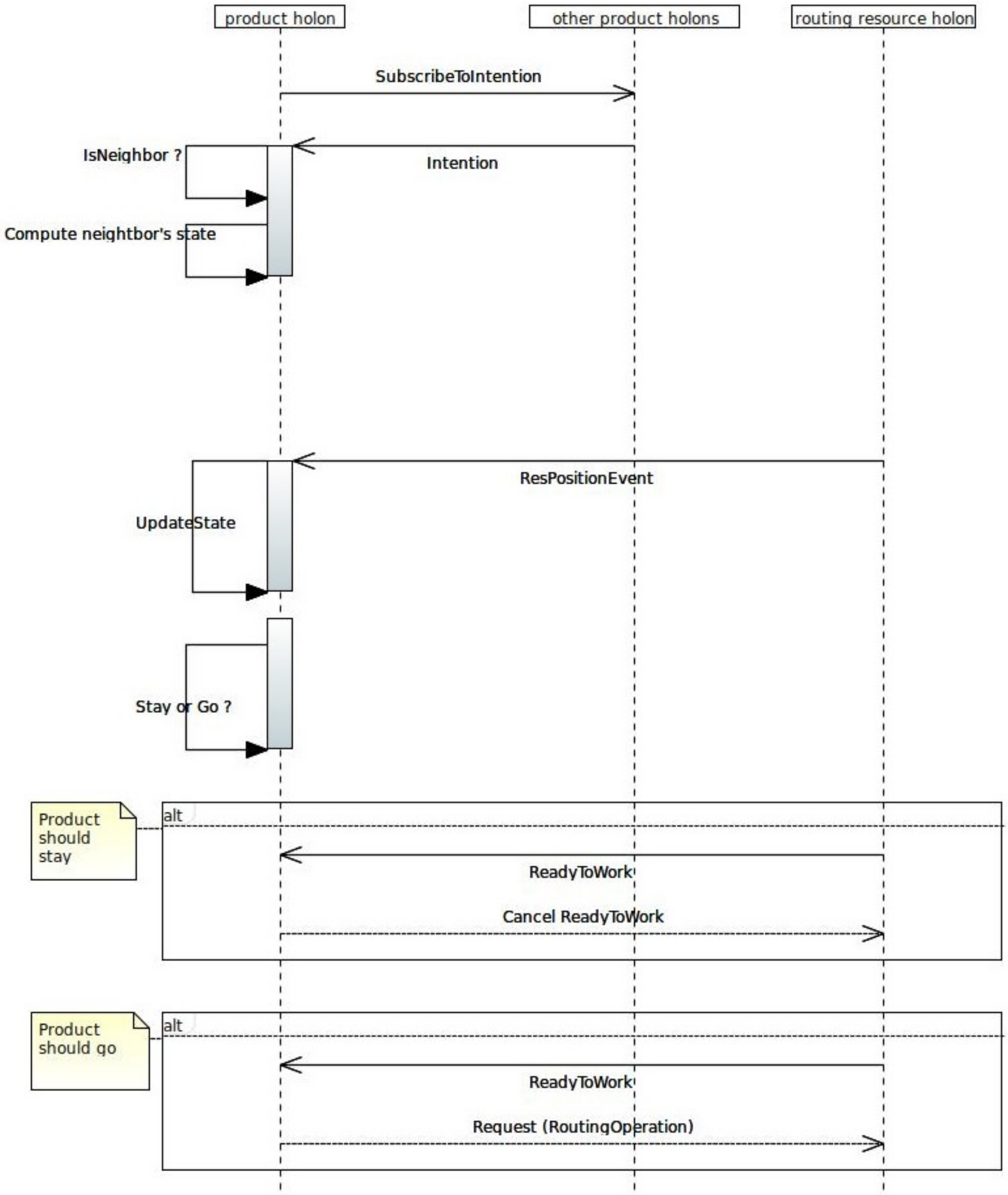


Figure 4.11: Consensus control sequence diagram

The *Negotiation* control mode is based on a *Contract Net*-like protocol [172]. Each time a product holon reaches a resource, a functional neighborhood is established, by grouping all product holons that will pass on this same resource in the future. Each product holon of the functional neighborhood computes its intentions as a set of 3 elements: estimated arrival date on the resource, required processing time, and estimated release date. These intentions are broadcast to the whole neighborhood, and to the concerned resource. Then, the resource uses a contract net-inspired algorithm to prioritizes the product holons' running order [119]. Figure 4.12 presents a sequence diagram of the interactions occurring when a product holon is reaching a resource one in negotiation control mode.

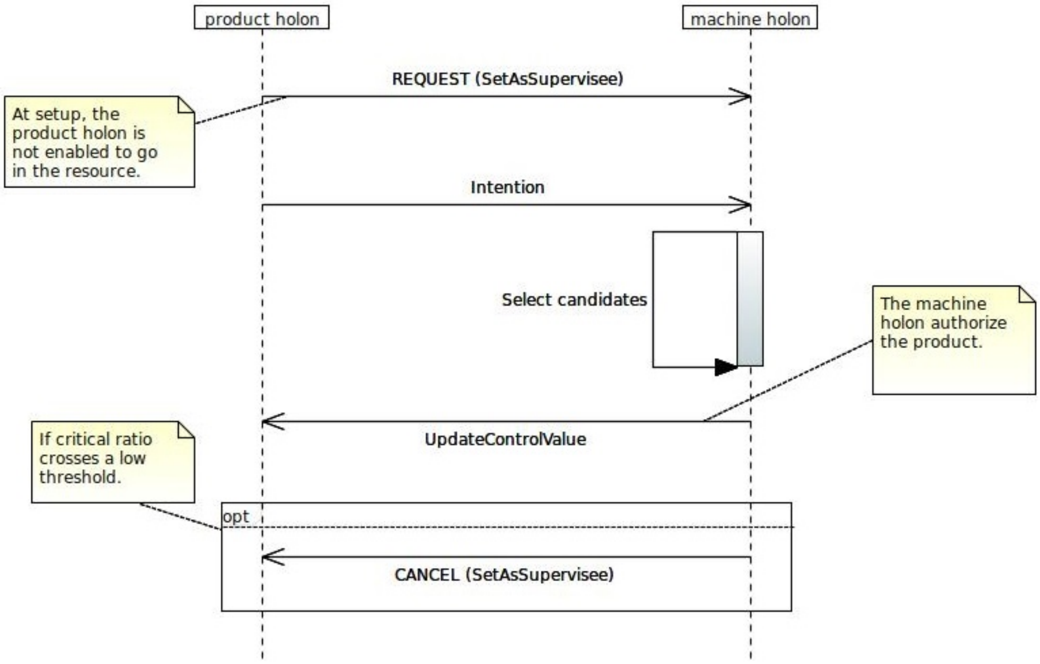


Figure 4.12: Negociation control sequence diagram

4.3 Instantiation

This section details the instantiation that has been performed on the TRACILOGIS test-bed platform, to make the proof-of-concept of the proposed formal framework for social holarchies modelling. More precisely, for convenience, the instantiating has been realized on a platform's emulation, based on messages exchanges recorded on the physical test-bed system. What will be studied here is the model's ability to express the different control modes, from a social viewpoint. Hence, after detailing the basic steps followed by a reactive-controlled holon during its lifetime, what will be studied is the expressiveness of the model regarding the control modes' specific behaviors. More precisely, decision-modes will be modelled during a product's visit of resource $M1$, for this step is the one where negotiation control shows its full potential, and is therefore the most relevant to be considered.

Figure 4.15 provides an illustration of the way relationships' establishment have been instantiated, depending on the control mode. The relationship state machines supporting this instantiation are detailed in the appendix A. Equally, the nature of events and signals relating to these are respectively presented in appendixes B and C. On this diagram, zone 1 represents the potential inter-holons relationship established for pure reactive control mode. Zone 2 and 3 respectively introduce the subclasses that are adding to and extending reactive mode for consensus and negotiation ones. Thus, the instantiation of the one or the other of control modes is simply achieved by using the corresponding class. In absolute, it would be possible for both consensus and negotiation control modes to be simultaneously implemented. In this study though, it has been chosen to exclusively instantiate those separately. Zone 4 is grouping the features that are common to consensus and negotiation modes. Notably, the class "*MachineHolon*" is extending the "*ResourceHolon*" one, conferring collaboration abilities to resource performing more that routing transformations (i.e. $Mq1$, $Mq2$, $M1$, and $M2$). The "*IntentionProductHolon*" is representing the product holons' ability to plan and communicate their intentions (path) to their neighbors (see fig.4.13).

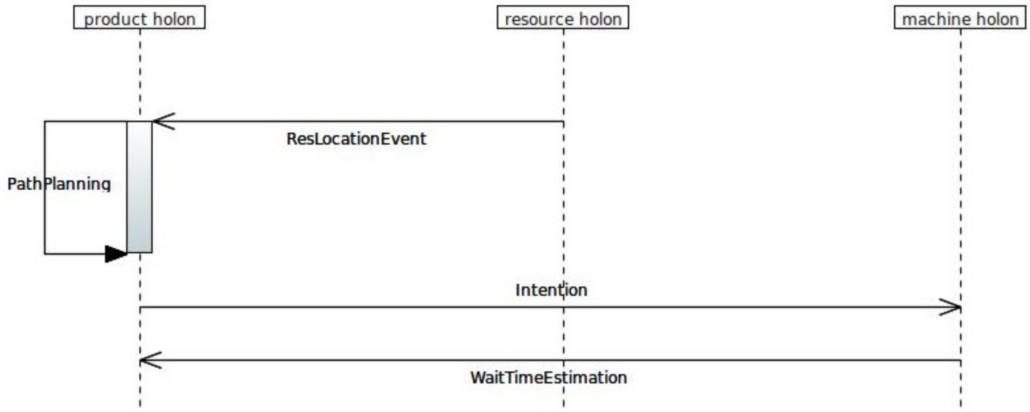


Figure 4.13: Intentions and wait time estimation sequence diagram

In this study, 3 types of direct relationships are involved, along with their depending emergent relationships i.e. $C-HR$, $C-DR$ and $C-OR$. Therefore, 6 types of social relationships will be observable. More precisely, the following direct relationships can be instantiated through the developed study case (Fig. 4.15):

- HR between the $ProductLauncher$ and the $ProductHolon$ types: when the product receive its objectives (configuration, due date, etc.);
- HR between the $ProductHolon$ and the $ResourceHolon$ types: when the product requests the resource to execute operation (routing, machining, assembling);
- OR between the $ProductHolon$ and the $ResourceHolon$ types: when a product is inside a resource's action area;
- HR and DR between the $ResourceHolon$ and the $PlcHolon$ types: when the resource requests the physical actuation from the PLC;
- DR between the $ResourceHolon$ and the $RfidHolon$ types: when the resource request information concerning the product to the RFID;
- DR between the $IntentionProductHolon$ and the $MachineHolon$ types: when products are sending their intentions to resources;
- DR between the $ConsensusProductHolon$ type and itself: when products are sharing their intentions with each others;
- HR between the $NegoProductHolon$ and the $MachineHolon$ types: when product requests the resource to execute operation (in the case of negotiation).

No Parental Relationship have been here implemented. This relationship appears as soon as a common characteristic is to be found among two holons. Hence, at some point, any resources will be in C-PR with other ones, and the same will go between products. For instance, considering figure 4.14 presenting the representation of 3 product holons into the platform's emulation, each one of the 4 identified levels could be considered as defining a C-PR-zone among holons. And for each of these levels, stronger C-PR could be identified among more specific types of holons: products depending on their configuration, resource according to their types (mergers, splitters, assembly or machining station, plc, rfid, etc.). Besides, the structural aspect of PR makes it a relationship which will a priori be less likely to change over time. Hence, to relevantly study the appearance and disappearance of PR among the system's holons, additional development around the notions of Relationship Degree and Relationship Intensity would be required.

Equally, the Dependency Relationship between product and resource holons is not modelled. This relationship between products and resources is fundamental in product-driven systems, for products are dependent from resources to be processed. The instantiated control mode aim to provide an optimal way to fulfill this dependency. For this reason, the DR between products and resources is considered as structural in the system, and not relevant to be represented here.

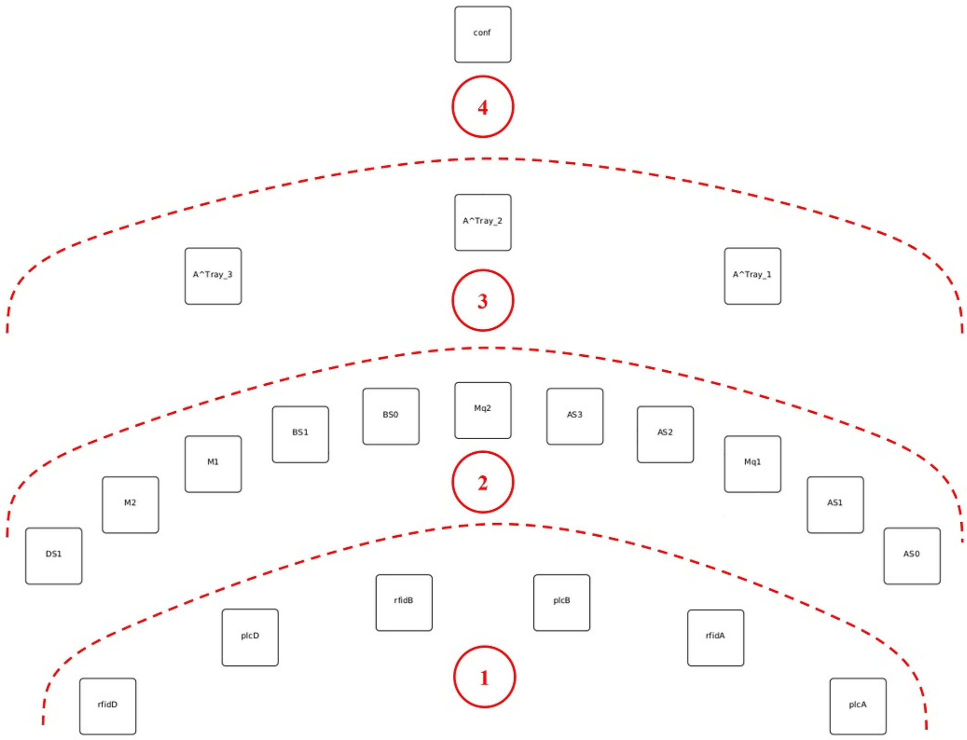


Figure 4.14: System's emulation representation

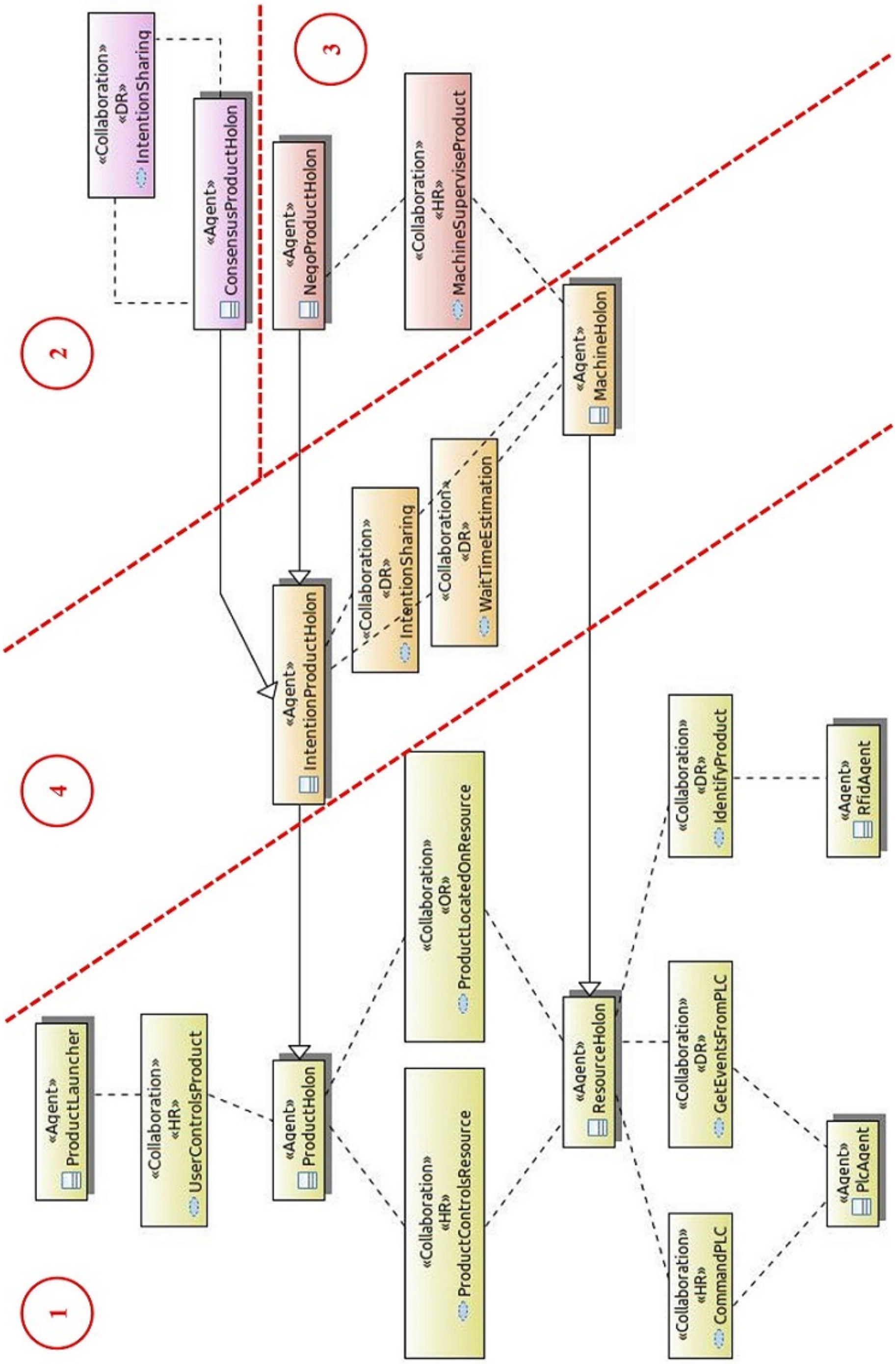


Figure 4.15: Potential relationships among holons types

4.3.1 Product holon's lifecycle

The basic steps followed by a product holon during its lifespan are:

- Step 1: At creation, the product holon searches the *DF* to find resources and event sources;
- Step 2: When notified that it is in front of a manufacturing cell, the product holon requires the corresponding resource holon to execute its next operation;
- Step 3: If the resource holon is able to perform the operation, it agrees and sends a sequence of action requests to the PLC holons;
- Step 4: If not, it refuses the request
- Step 5: When the product holon is finished, or if no operation can be executed in the cell, it requests the cell to release it

Steps 2 to 5 are repeating themselves as long as the product holon has not reached its completion (i.e., is not in its desired final configuration). The product holon's death would consist in a 6^{th} step. Yet, this one is not here represented, for it would simply consist in relationships disappearance.

First, a product holon ${A^{\text{Tray}}}_1$ is created through the *ProductLauncher*. From its creation, all of ${A^{\text{Tray}}}_1$'s potential relationships with its ecosystem are generated: HR between the product launcher and the product, OR and HR between the resource and the product, and DR between the product and the operating system (RFID and PLC). In this study, the operating system is emulated, and thus represented by the *EMU* holon. This last one is needed by the product holon, for it provides it all its related events: $\mathcal{R}^{DR}_{{A^{\text{Tray}}}_1 \xrightarrow[DEPENDENT]{} EMU} = 1$. If the system would not have been emulated, the very same relationship would have been established between product holon and PLC & RFID agents.

When arriving in front of a manufacturing cell ${A^{\text{Resource}}}_1$, the product holon is notified by *EMU* through their existing *DR* relationship (${A^{\text{Tray}}}_1$ depends on *EMU* to know its location). At this time, ${A^{\text{Tray}}}_1$ requests ${A^{\text{Resource}}}_1$ to execute operation. In the same time, at the very moment it enters the resource's actuation zone ${A^{\text{Tray}}}_1$ establishes an Ownership Relationship with the resource: $\mathcal{R}^{OR}_{{A^{\text{Resource}}}_1 \xrightarrow[OWNER]{} {A^{\text{Tray}}}_1} = 1$, where ${A^{\text{Tray}}}_1$ becomes owned by ${A^{\text{Resource}}}_1$. This *OR* is expressed through the *ResourceLocationEvent*, and then the R2W information send by the resource to the product. Once the resources have send its readiness to work, the product holons send back an operation request, expressed by the creation of a HR between the two of them, noted: $\mathcal{R}^{HR}_{{A^{\text{Tray}}}_1 \xrightarrow[SUPERIOR]{} {A^{\text{Resource}}}_1} = 1$, where ${A^{\text{Tray}}}_1$ becomes the superior of ${A^{\text{Resource}}}_1$.

If ${A^{\text{Resource}}}_1$ is able to perform the requested task, it sends a sequence of action requests to the *EMU* for "effectively perform" the operation. The resource holon commands to the physical system and hence establish a Hierarchical Relationship with it. In this scenario, ${A^{\text{Resource}}}_1$ becomes the superior of *EMU*, noted: $\mathcal{R}^{HR}_{{A^{\text{Resource}}}_1 \xrightarrow[SUPERIOR]{} EMU} = 1$. Relationships between the product and resource holons are disappearing (i.e., their degree set to 0) once the task is completed (i.e., INFORM(Done) messages transmitted from EMU to resource, and from resource to product).

These relationships are those established by the product holon with its ecosystem during its lifetime regardless of the control type. Yet, as seen before, more relationships can be identified within the system.

4.3.2 Reactive control

Reactive control instantiation is performed thanks to the 3 product holons detailed in figure 4.16. Besides, products' launch, estimated completion, and actual completion dates are detailed by table 4.4, and their passing sequence on each resource illustrated by the Gantt diagram on figure 4.17. In this scenario, the completion of the 3 product holons ${A^{\text{Tray}}}_1$, ${A^{\text{Tray}}}_2$, and ${A^{\text{Tray}}}_3$ is achieved in this order.

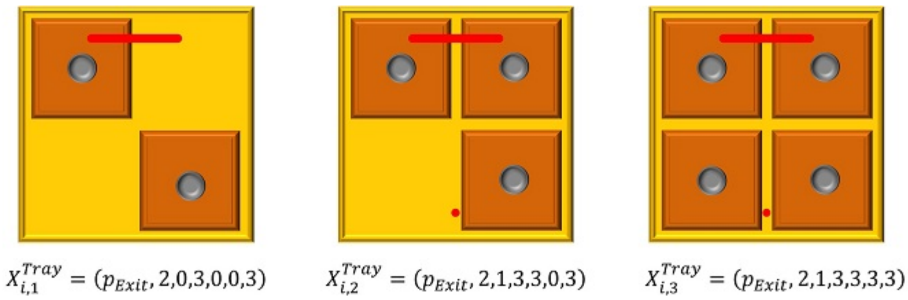


Figure 4.16: Product holon's configuration for reactive control

Table 4.4: Configurations and processing times for reactive control

Products Configuration	Launch Date	Completion Date
${\mathcal{X}^{\text{Tray}}}_{i,1} = (p_{Exit}, 2, 0, 3, 0, 0, 3)$	0	223
${\mathcal{X}^{\text{Tray}}}_{i,2} = (p_{Exit}, 2, 1, 3, 3, 0, 3)$	6	349
${\mathcal{X}^{\text{Tray}}}_{i,3} = (p_{Exit}, 2, 1, 3, 3, 3, 3)$	13	383

Figure 4.18 provides an overview of the relationships existing between the system's holons at the time products holons ${A^{\text{Tray}}}_2$ and ${A^{\text{Tray}}}_3$ are both passing through resource $M1$. Only the 2 product holons, ${A^{\text{Tray}}}_2$, and ${A^{\text{Tray}}}_3$ are still existing in the system (i.e., does not have completed their configuration). They are consequently both hierarchically controlled by the *ProductLancher* agent ("prod_launcher" on the figure). *ProductLancher* is responsible for the creation of product holons and is the one providing them their objective (desired configuration). It is equally informed at each of their change of state. This relationship is disappearing as soon as the fabrication process is over (i.e., when the product holon casts its actual completion date). Hence, the following

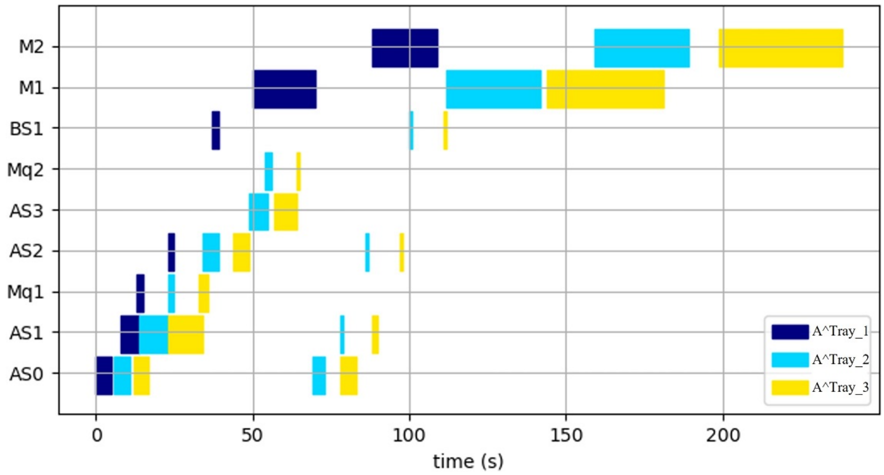


Figure 4.17: Gantt diagram of reactive control instantiation

relationships are existing:

$$\begin{cases} \mathcal{R}^{HR}_{ProductLancher \xrightarrow[SUPERIOR]{} A^{\text{Tray}_2}} = 1 \\ \mathcal{R}^{HR}_{ProductLancher \xrightarrow[SUPERIOR]{} A^{\text{Tray}_3}} = 1 \\ \mathcal{R}^{C-HR}_{A^{\text{Tray}_2} \Longleftrightarrow A^{\text{Tray}_3}} = 1 \end{cases}$$

Resource holons require gateway holons, such as PLC and RFID (or their emulator), both for event detection from or event transmission to the operating system. Concerning RFID holons, their relationships with resource holons are only established when at the initiative of these last ones (ProductEvent Queries). Concerning PLC holons, those are both related to the platform's proximity sensors that are continuously informing the resource holon of the presence or absence of product, and to the actuators enabling resources to effectively perform actions. Hence, a DR is permanently existing between PLC holons and resource ones, while holons depending from a same PLC are in C-DR.

At the time of figure 4.18, while A^{Tray_3} is in front of $M1$, A^{Tray_2} is inside of the resource and being processed. This situation implies that both A^{Tray_2} and A^{Tray_3} are owned by $M1$ (C-DR) while only A^{Tray_2} is hierarchically superior to it. Equally, since $M1$ requires *plcD*'s action to process A^{Tray_2} (DR), it therefore establishes a HR to command and obtain it. Thus following

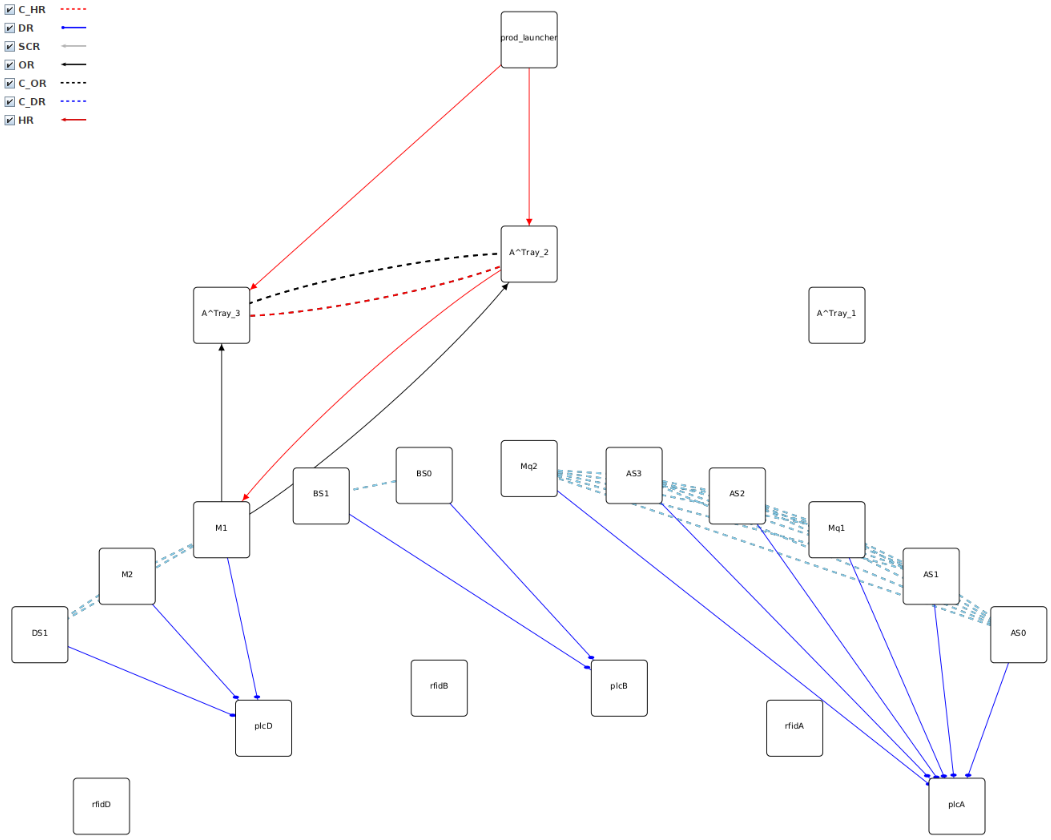


Figure 4.18: Graph of relationships, in reactive control mode, when $A^{\text{Tray}}{}_2$ is being processed by $M1$, and $A^{\text{Tray}}{}_3$ is waiting for $M1$

relationships are existing:

$$\begin{cases} \mathcal{R}^{HR}_{A^{\text{Tray}}{}_2 \xrightarrow[SUPERIOR]{} M1} = 1 \\ \mathcal{R}^{OR}_{M1 \xrightarrow[OWNER]{} A^{\text{Tray}}{}_2} = 1 \\ \mathcal{R}^{OR}_{M1 \xrightarrow[OWNER]{} A^{\text{Tray}}{}_3} = 1 \\ \mathcal{R}^{C-DR}_{A^{\text{Tray}}{}_2 \Longleftrightarrow A^{\text{Tray}}{}_3} = 1 \\ \mathcal{R}^{DR}_{M1 \xrightarrow[DEPENDENT]{} plcD} = 1 \\ \mathcal{R}^{HR}_{M1 \xrightarrow[SUPERIOR]{} plcD} = 1 \end{cases}$$

4.3.3 Consensus control

Consensus control instantiation is performed thanks to the 3 product holons detailed in figure 4.19. Besides, products' launch, estimated completion, and actual completion dates are detailed by table 4.5, and their passing sequence on each resource illustrated by the Gantt diagram on figure 4.20. In this scenario, it can notably be seen that the product holon $A^{\text{Tray}}{}_1$ is routed to the buffer zone to let the priority to $A^{\text{Tray}}{}_3$.

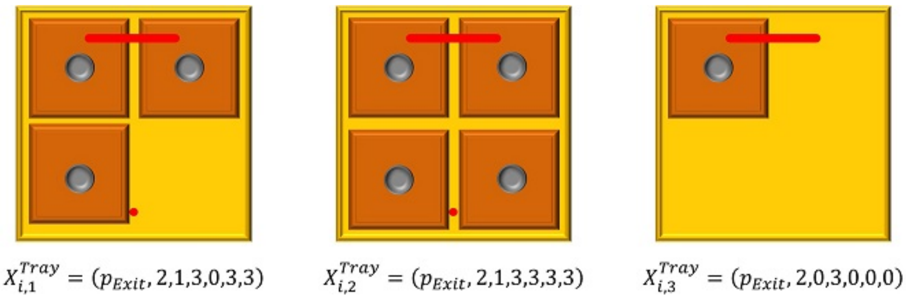


Figure 4.19: Product holon's configuration for consensus control

Table 4.5: Configurations and processing times for consensus control

Products Configuration	**Launch Date**	**Completion Date**
$\mathcal{X}^{\text{Tray}}{}_{i,1} = (p_{Exit}, 2, 1, 3, 0, 3, 3)$	0	298
$\mathcal{X}^{\text{Tray}}{}_{i,2} = (p_{Exit}, 2, 1, 3, 3, 3, 3)$	7	250
$\mathcal{X}^{\text{Tray}}{}_{i,3} = (p_{Exit}, 2, 0, 3, 0, 0, 0)$	53	264

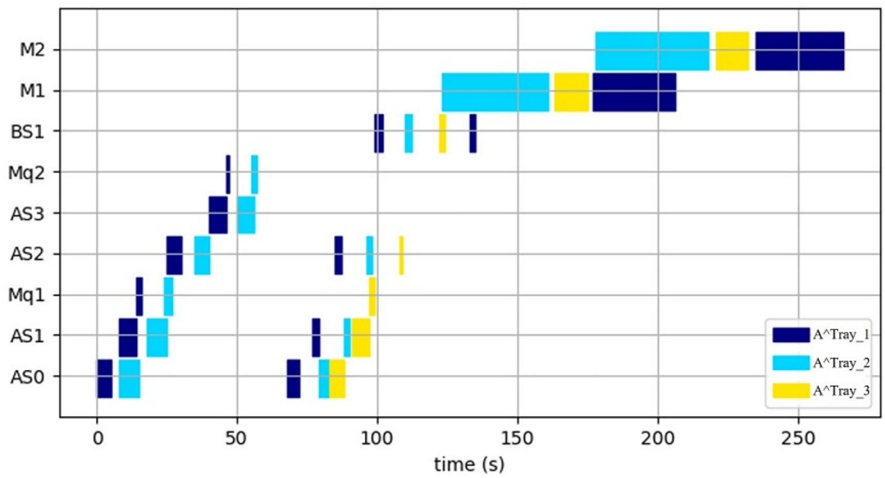


Figure 4.20: Gantt diagram of consensus control instantiation

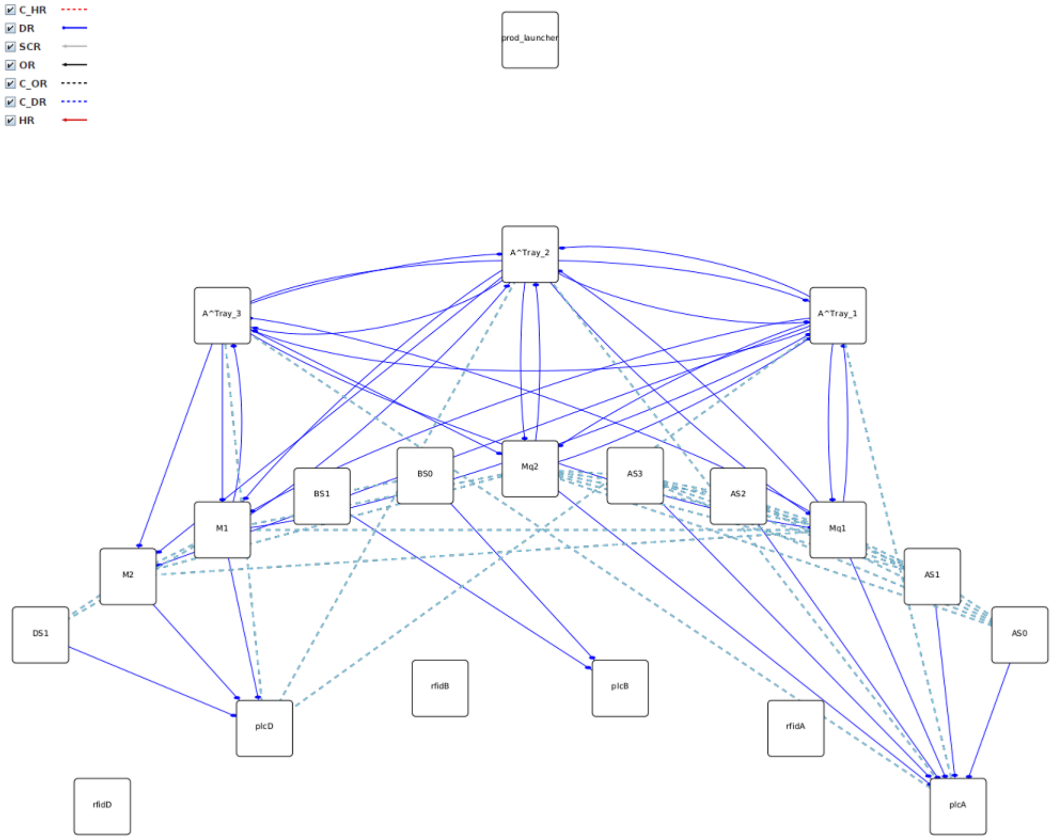


Figure 4.21: Graph of Dependency relationships, in consensus control mode, when $A^{\text{Tray}}{}_2$ is being processed and $A^{\text{Tray}}{}_3$ is waiting

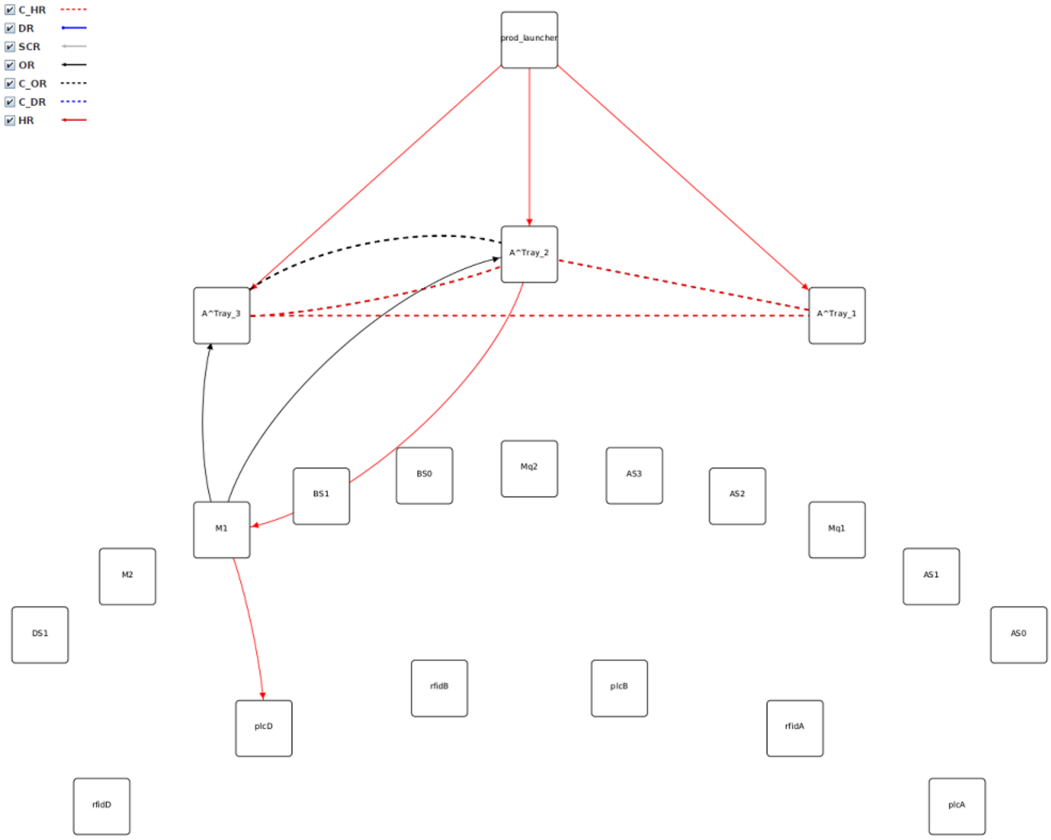


Figure 4.22: Graph of Hierarchical and Ownership relationships, in consensus control mode, when ${A^{\mathrm{Tray}}}_2$ is being processed by $M1$, and ${A^{\mathrm{Tray}}}_3$ is waiting for $M1$

As for the reactive case, at the time of figures 4.21 and 4.22, $A^{\text{Tray}}{}_2$ is inside of the resource $M1$ and being processed, while $A^{\text{Tray}}{}_3$ is in front of it. This situation implies the exact same relationships than those seen in reactive control for consensus control is an extension of it. This being said, the negotiation control is expressed by the appearance of several additional DR and HR. For better visualization, it has been chosen to separate DR from the other ones.

First, reciprocal DR are established among each product holon, corresponding to intention exchanges. Indeed, these intentions are mandatory for a product holon facing a resource to determine its neighbors, to perform consensus algorithm. In the studied situation, $A^{\text{Tray}}{}_3$ is the agent triggering the consensus algorithm while reaching $M1$: Hence, $A^{\text{Tray}}{}_3$ is dependent of all other product holons $A^{\text{Tray}}{}_i$ and reciprocally.

Second, others reciprocal DR are established among neighbor holons and the resource ones. Products are dependent on resources to get an estimation of waiting time before entering, enabling them calculate an estimation of their travel time (mandatory for optimization). Conversely, resources are dependent on products to get their intentions and keep the program of product visits up to date. These relationships are established all across the system each time a product reaches a resource. In the studied situation, resource $M1$ is then dependent of all product holons $A^{\text{Tray}}{}_i$ and reciprocally.

All these relationships can be expressed by the list below. Naturally, these relationships have to be considered along with their related co-relationships. Those being numerous, they are not listed here.

$$\begin{cases} \mathcal{R}^{DR}_{A^{\text{Tray}}{}_3 \xrightarrow[DEPENDENT]{} A^{\text{Tray}}{}_i} = 1 \\ \mathcal{R}^{DR}_{A^{\text{Tray}}{}_i \xrightarrow[DEPENDENT]{} A^{\text{Tray}}{}_3} = 1 \\ \mathcal{R}^{DR}_{M1 \xrightarrow[DEPENDENT]{} \text{Tray}_i} = 1 \\ \mathcal{R}^{DR}_{A^{\text{Tray}}{}_i \xrightarrow[DEPENDENT]{} M1} = 1 \end{cases}$$

4.3.4 Negotiation control

Negotiation control instantiation is performed thanks to 9 product holons, in a same configuration, detailed in figure 4.19. Products' launch, estimated completion, and actual completion dates are detailed by table 4.5, and their passing sequence on each resource illustrated by the Gantt diagram of figure 4.20.

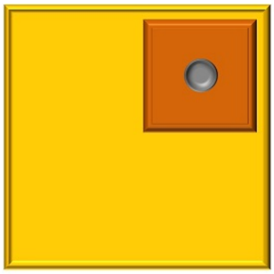


Figure 4.23: Product holon's configuration for negotiation control

Table 4.6: Configurations and processing times for negotiation control

Products Configuration	**Launch Date**	**Completion Date**
$\mathcal{X}^{\text{Tray}}{}_{i,1} = (p_{Exit}, 0, 0, 0, 3, 0, 0)$	0	115
$\mathcal{X}^{\text{Tray}}{}_{i,2} = (p_{Exit}, 0, 0, 0, 3, 0, 0)$	6	129
$\mathcal{X}^{\text{Tray}}{}_{i,3} = (p_{Exit}, 0, 0, 0, 3, 0, 0)$	12	144
$\mathcal{X}^{\text{Tray}}{}_{i,4} = (p_{Exit}, 0, 0, 0, 3, 0, 0)$	24	202
$\mathcal{X}^{\text{Tray}}{}_{i,5} = (p_{Exit}, 0, 0, 0, 3, 0, 0)$	22	173
$\mathcal{X}^{\text{Tray}}{}_{i,6} = (p_{Exit}, 0, 0, 0, 3, 0, 0)$	28	188
$\mathcal{X}^{\text{Tray}}{}_{i,7} = (p_{Exit}, 0, 0, 0, 3, 0, 0)$	34	227
$\mathcal{X}^{\text{Tray}}{}_{i,8} = (p_{Exit}, 0, 0, 0, 3, 0, 0)$	40	158
$\mathcal{X}^{\text{Tray}}{}_{i,9} = (p_{Exit}, 0, 0, 0, 3, 0, 0)$	47	241

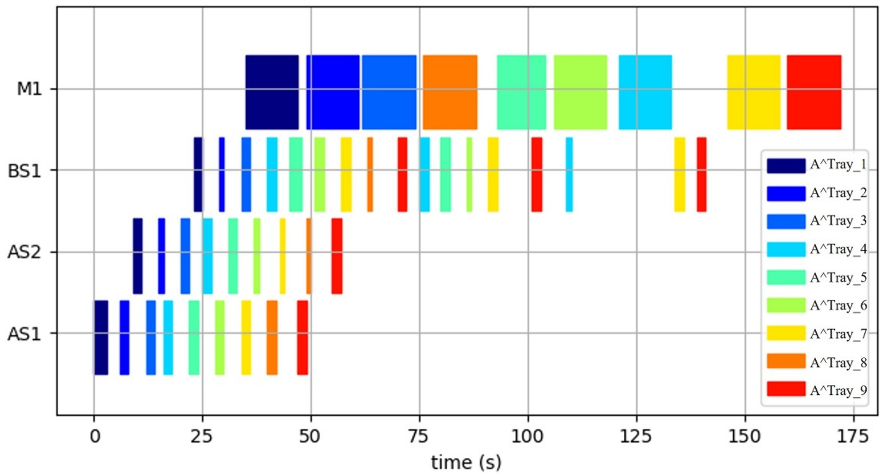


Figure 4.24: Gantt diagram of negotiation control instantiation

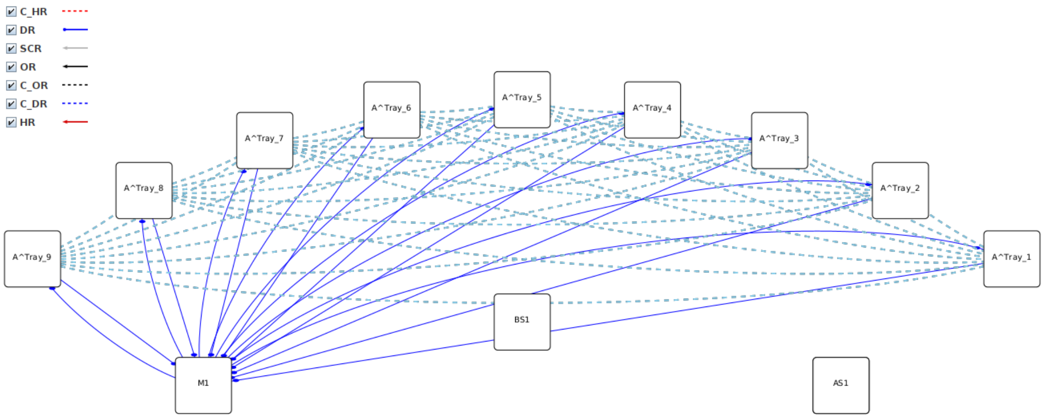


Figure 4.25: Graph of Dependency relationships, in negotiation control mode, when ${A^{\text{Tray}}}_8$ is being processed by $M1$, and ${A^{\text{Tray}}}_5$ is reaching $BS1$

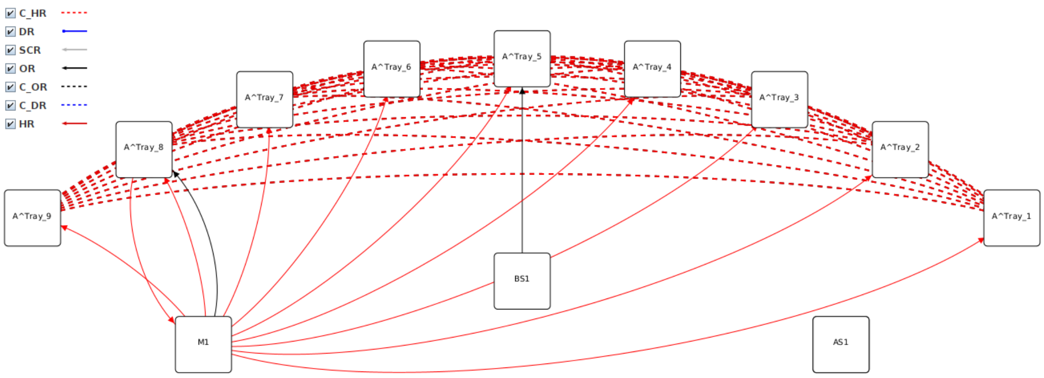


Figure 4.26: Graph of Hierarchical and Ownership relationships, in negotiation control mode, when ${A^{\text{Tray}}}_8$ is being processed by $M1$, and ${A^{\text{Tray}}}_5$ is reaching $BS1$

Once again, the system is considered at the level of resource $M1$. In this situation, at the time of figures 4.25 and 4.26, the product holon A_8^{Tray} is processed while the A_5^{Tray} one is reaching the resource $BS1$. Yet, if negotiation control is an extension of reactive one, it does not imply all the same relationships. For better visualization, it has been chosen to separate DR from the other HR and OR ones. Equally, to avoid visual overload, only 2 of the resources holons have been tracked: $M1$ and $BS1$. *Product Laucher* is equally not represented. However, even if not represented, the previously-mentioned DR, C-DR, HR, and C-HR relationships binding them while performing their functions are existing and shall be kept in mind.

First, reciprocal DR are observable between all active product holons and the resource holon $M1$. Products are dependent on $M1$ to get an estimation of waiting time before entering, enabling them calculate an estimation of their travel time (mandatory for optimization). Conversely, $M1$ is dependent on products to get their intentions and keep the program of product visits up to date. These relationships are established all across the system each time a product reaches a resource. In the studied situation, resource $M1$ is then dependent of all product holons ${A^{\text{Tray}}}_i$ and reciprocally, and all product holons ${A^{\text{Tray}}}_i$ are in C-DR with each others (see Fig. 4.25).

Second, the negotiation control mode implies a control by the resource of neighbor holons, to run the negotiation algorithm. Thus, each time a product holon reaches a resource (performing more that routing transformations (i.e., $Mq1$, $Mq2$, $M1$, or $M2$), all products are notifying the resource of their hierarchical submission. In the studied situation, product holons ${A^{\text{Tray}}}_i$ become subordinated to $M1$, and thus, in C-HR with each others. Besides, resource $M1$ is a bit specific for it is equally performing routing operations. Hence, regarding processing operations, $M1$ is hierarchically superior to the product holon ${A^{\text{Tray}}}_8$ that is being processed. Meanwhile, ${A^{\text{Tray}}}_8$ is hierarchically superior to $M1$ regarding routing operations.

Finally, ${A^{\text{Tray}}}_8$ is of course owned by $M1$. Equally, at the considered moment, it can be seen that product holon ${A^{\text{Tray}}}_5$ is currently owned by $BS1$. Hence, it can be established that, at this moment, while ${A^{\text{Tray}}}_8$ is being processed by $M1$, ${A^{\text{Tray}}}_5$ is reaching $BS1$, either to be routed toward $M1$, or toward the buffer zone (back to $BS0$).

All these relationships can be expressed by the list below. Naturally, these relationships have to be considered along with their related co-relationships. Those being numerous, they are not listed here.

$$\begin{cases} \mathcal{R}^{HR}_{M1 \xrightarrow[SUPERIOR]{} {A^{\text{Tray}}}_i} = 1 \\ \mathcal{R}^{HR}_{{A^{\text{Tray}}}_8 \xrightarrow[SUPERIOR]{} M1} = 1 \\ \mathcal{R}^{OR}_{M1 \xrightarrow[OWNER]{} {A^{\text{Tray}}}_8} = 1 \\ \mathcal{R}^{OR}_{BS1 \xrightarrow[OWNER]{} {A^{\text{Tray}}}_5} = 1 \\ \mathcal{R}^{DR}_{M1 \xrightarrow[DEPENDENT]{} {A^{\text{Tray}}}_i} = 1 \\ \mathcal{R}^{DR}_{{A^{\text{Tray}}}_i \xrightarrow[DEPENDENT]{} M1} = 1 \end{cases}$$

4.4 Discussion

This sections aims to deepen the proof-of-concept brought by the 3 above-mentioned instantiations. The "expressiveness" of the social model proposed in this Ph.D thesis dissertation has been proved. The creation and disappearance of different social relationships among the system at run time can be visualized, and can even make it possible to identify the type of control mode in action. What is initiated here is to estimate the complexity reduction allowed by the social model, and its propensity to facilitate the apprehension of the communication between a system's holons by the human operator. To do so, the number of relationships establishment and disappearance among the system, for each of the 3 scenarios previously instantiated, have been counted (tables 4.7 and 4.8), along with the number of exchanged messages (table 4.9).

First thing that can be noted is the fact that, depending on the control mode, relationships are not quite established the same way. Notably, it seems that negotiation mode implies more C-HR, and less OR than reactive and consensus ones. Equally, there are in each case less disabled relationships than established ones. This could be explained by the presence of both structural relationships and conjunctural ones. Structural relationships are established at the system's initialization, and for the whole duration of the scenario (e.g.: DR between resource holon and plc agent). Conjunctural relationships are closely related to the *Dynamic* nature of the social framework for HCA proposed in this dissertation. These are situationally established among two holons and dismissed as soon as the situation is over (e.g., OR between a product and a resource holons).

Table 4.7: Number of established relationships per type and per scenario

	Reactive	**Consensus**	**Negotiation**
HR	77 (*36%*)	87 (*31%*)	109 (*30%*)
C-HR	16 (*7%*)	20 (*7%*)	53 (*14%*)
OR	34 (*16%*)	35 (*12%*)	21 (*6%*)
C-OR	1 (*1%*)	4 (*2%*)	3 (*1%*)
DR	42 (*20%*)	62 (*22%*)	78 (*21%*)
C-DR	42 (*20%*)	74 (*26%*)	104 (*28%*)
Total	***212***	***282***	***368***

Second thing to be noted is that, in the considered scenarios, there are between 70% and 85% less created relationships than exchanged messages. To observe the interactions among a system, and therefore to understand its functioning, the use of message traces lead the human user to read and analyze hundreds or thousands of lines of messages, written in software language. By enabling the aggregation of these messages and their visual restitution, it can be estimated that the use of the social framework proposed in this work considerably reduces the perceived complexity of a system's functioning.

These two elements only constitute a first approach for this social model exploitation, and are rapidly suffering from the study perimeter limits. Notably, the reduced number of scenarios used (3), and the fact they have each been instantiated trough a different control mode notably raise two issues. In the one hand, an extensive study of the social model's expressiveness regarding

Table 4.8: Number of disabled relationships per type and per scenario

	Reactive	**Consensus**	**Negotiation**
HR	77 (*46%*)	87 (*40%*)	108 (*34%*)
C-HR	16 (*10%*)	20 (*9%*)	53 (*17%*)
OR	34 (*20%*)	35 (*16%*)	21 (*7%*)
C-OR	1 (*0%*)	4 (*2%*)	3 (*1%*)
DR	19 (*12%*)	25 (*12%*)	52 (*16%*)
C-DR	19 (*12%*)	45 (*21%*)	78 (*25%*)
Total	***166***	***216***	***315***

Table 4.9: Number of exchanged messages vs. number of established relationships per scenario

	Exchanged Messages	**Established Relationships**	***Ratio Rel.\Mess.***
Reactive	767	212	*27,6%*
Consensus	1920	282	*14,7%*
Negotiation	1925	368	*19,1%*

ones control mode in various situation is impossible. This would have only been possible with the instantiation of multiple scenarios regarding one single control mode. In the other hand, the demonstration of the social model's relevance to compare various control modes in a same situation is not supported. This would have implied the instantiation of a same scenario regarding the different control modes. Thus, first future works should aim to instantiate various scenarios to all the 3 control modes presented here. Equally, even if visualization of interactions among the system has been eased, the number of visible relationships and information on graph is still too large to provide real ease of reading.

4.5 Chapter conclusion

This chapter has brought the proof-of-concept for the social holonic formal model proposed in chapter 3. After detailing the CRAN's TRACILOGIS technical platform, from its operating to its control system, three instantiation have been performed. These have shown the feasibility of dynamically representing the structure of a system with a typology of social relationships. Three control approaches for PDS have been instantiated (reactive, consensus, and negotiation), each through a different scenario. For each of those, the different observable relationships have been described and explained. Thus, a first approach for numerical analysis of social HCA's instantiation have been exposed.

If this chapter has provided a certain number of results, it can already be stated that further studies are needed. Notably, more research is needed to propose a relevant instantiation of PR and C-PR relationship. Equally, involving more holons/agents through more numerous and complex scenarios should be undertaken. This will allow a more complete study of the proposed model. Additional developments could then be considered, for instance focusing on the notions of relationship degree and intensity, to reduce even more the system's complexity. Future works will also have to focus on assessing the potential of this social framework as a decision-making support/enabler through the development of notions such as reputation or trustworthiness. Finally, an evaluation framework should be developed to qualify and quantify the social framework's benefits in terms accessibility, explainability, and acceptability regarding the human factor into manufacturing systems.

Chapter 5

General conclusion and outlook

"[...]mais en dépit de tout cela, en bref, au juste et en définitive, à quoi sert-il ? Pour pertinente qu'elle soit, cette question ne comporte pas de réponse. Car le grand, l'immense mérite, des deux illustres savants qui sont les frères Fauderche, réside principalement dans leur magnifique esprit de désintéressement, puisque faisant uniquement de la science pour la science, comme d'autres font de l'Art pour l'Art, ils n'ont jamais et à aucun moment, envisagé le côté bassement utilitaire de leur généreuse et gratuite invention."

Le Schmilblick, Pierre Dac, 1950

Last decades have seen the growth in size and complexity of industrial systems, the emergence of new consumption modes, and the rise & strong developments of Information Technologies. In this context, national and international initiative and programs such as the IMS ones, Industry 4.0, or even Industry 5.0 have aimed to help industrial systems to adapt and equip themselves to overcome their current and future challenges. Hence, flexibility, efficiency and resiliency have become the key words for the future of manufacturing systems. On this subject, the work of the CRAN and others laboratories has made it possible to establish the following elements: the relevance of hybrid manufacturing control architectures, the potential of holonic approaches, and the centrality of the human factor. In this Ph.D thesis project, this assertion have led to consider the 2 following research questions:

- [QR1] How to take advantage from the new concepts introduced by Industry 4.0, such as the IoT and CPS paradigms, for the development of future manufacturing control architectures?
- [QR2] How to get the human better integrated in future manufacturing systems, as socio-technic ones?

These two questions have then be studied through several iterations of literature review and analysis, notably questioning the place given to the human into current and future industrial systems. Many technological advances have been retrieved trough these studies, proving that manufacturing environment are more than ever to be perceived and treated as complex socio-technical systems, notably in holonic research field. Yet, many gaps are still to be bridged. Despite the great potential of HCA, literature relating to their developments have shown a certain lack of formalism. Notably, the definition of their structure / inter-holons relationships is generally limited to the notions of aggregation, hierarchy or data exchanges directly abstracted from a specific study system. Hence, the lack of a generic formal framework for architecture or systems representation and design in current literature is a first point. The study of the human aspect into IoT and CPS paradigms, as grounding concepts structuring most of current Industry 4.0 -related technological developments, have led to the conclusion that these aspects were expressed through 3 types of sociability, supporting 4 types of socio-technical systems. Those can be classified as systems of (1) *communicating objects*, (2) *communicating objects interacting with humans*, (3) *communicating objects structured as a social network*, and (4) *communicating objects and humans structured as a social network*.

These two statements have led to the following hypothesis: inspired from Industry 4.0 (and 5.0)'s grounding concepts, it appears that the use of human-inspired social relationship to structure a system as a social network of communicating objects/agents and human could ease the design of systems as socio-technic ones, and therefore favor HSI. Besides, the holonic paradigm being widely proven as supportive for hybrid control architectures development, a social formal framework for HCA design and visualization has been proposed in this Pd.D thesis, as a way to bring an answer to the two research questions exposed here-above. To do so, a social HCA reference framework is exposed through the notions of "*components*", "*structure*", "*behaviors*", and "*dynamics*". In this framework, a typology based on 4 fundamental inter-holons *Direct Relationships* (namely *Parental Relationship*, *Ownership Relationship*, *Dependency Relationship*, and *Hierarchical Relationship*), along with their related *Emergent Relationships* have been proposed. Then, their formal model, along with a modeling and visualization software tool have been developed and detailed. The proof-of-concept for this social holonic formal model is then brought by its instantiation to the CRAN's TRACILOGIS technical platform through 3 scenarios, and for 3 different control modes (reactive, consensus, and negotiation). Finally, a first analysis on this instantiation have been conducted to illustrate the relevance of the proposed approach, as well as to highlight future research leads.

On the one hand, the social HCA reference framework successfully enables the representation of any manufacturing system as a society of socially-related holons. The model shows a certain expressiveness, by dynamically and in real time enabling the visualization of relationships' establishment and disappearance across the studied system. Compared to the use of messages' traces, this method can be considered as far more user-friendly, for it provides immediate illustration, and does not involve to navigate through hundreds or thousands of software language-written lines of messages. Besides, the use of relationships have reduced by more than 70% the number of elements to be analyzed, compared to exchanged messages' trace. This could both be explained by an aggregation ability of the model, and by its targeted use of messages trace. Regarding the user, this enhances accessibility, and can therefore be seen as enhancing acceptability. On the other hand, this study has only been conduced on a restricted number of scenarios, implying few control modes, and where PR and C-PR relationships have been set aside. Equally, the only place given to human has been the one of the system's supervisor. Hence, if the proof-of-concept has been realized, further developments are therefore needed. Indeed, robustness will have to be tested through multiple scenarios, more complex, implying diverse control modes, and including human users at different levels. In some cases, combinatorial explosion is to be expected, and ways to deal with it will have to be imagined and tested. Overall, the technological limits for this model instantiation need to be explored. Notions of relationships' degree and intensity to estimate the strength of a relationship will have to be deepened, along with the concepts of "*structural*" and "*conjunctural*" relationships. This would for instance make it possible to determine activation thresholds for relationships, or to estimate trust levels among holons. Application could be found while searching for the most critical relationships within a system, and/or for control and decision-making processes. This could help finding the best trade-off between architectures' performances, complexity, and acceptability for the design of future manufacturing systems.

In this Ph.D dissertation, the subject of the place of human into tomorrow's industrial systems has been approached through the development of a social reference framework for holonic architectures design. However, the issue is much broader. Human-System Integration is not only intended to cope with magic-human or acceptability issues. The literature study have shown that questions such as shortage and ageing of the qualified workforce or the raise of quality, safety and security norms were heavily weighing on manufacturing systems and their future developments. These challenges are found at the heart of initiatives such as Industry 4.0, or other national equivalents. Hence, many other research axes that have intentionally been excluded in this study due to their techno-centricity, can nonetheless be envisioned.

Many recent technological advances, mostly dealing with the development of enabling / enhancing / supportive technologies & tools to deal with human's physical & cognitive abilities (embedded internet-connected devices, causal AI, DT, Augmented / Virtual / Mixed reality, etc.), are making the concept of Human-Centered Design credible. These technologies could bring a new tangibility to manufacturing systems and control, strengthening their acceptability. However new issues, such as data security and private life privacy, are negatively impacting this very same acceptability. Therefore, new challenges will consist in exploring new models for multimodal production lines' organization, which would be reconfigurable and connected through various levels of human-machine cooperation (all-automated, all-manual, hybrid). This would notably be enabled by adding physiological, psychological, and social dimensions to the Cyber and Physical worlds, for human-centered control systems setting up. This will be supported by the development of integrative and collaborative technologies, adding on the one hand virtual elements to the physical environment to facilitate learning and secure work, and on the other hand able of acquiring, processing and considering human physiological, psychological, and social characteristics into new organisation and control models. Finally, the place of human into tomorrow's industrial systems shall equally have to be tackled through societal prisms, such as governmental policies or ethics.

Scientific production

National and international conferences with reading committee

2018 – **International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing** (SOHOMA 18) (author - speaker) – Bergamo, Italy – Oral presentation, publication in proceedings – *Toward an anthropocentric approach for hybrid control architectures: Case of a furniture factory* – Valette Etienne, Bril El-Haouzi Hind, Demesure Guillaume and Boucinha Vincent

2020 – **International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing** (SOHOMA 20) (author - speaker) – Paris, France – Oral presentation, publication in proceedings – *Toward a Social Holonic Manufacturing Systems Architecture Based on Industry 4.0 Assets* – Valette Etienne, Bril El-Haouzi Hind and Demesure Guillaume

2020 – **13ème Conférence Internationale de Modélisation, Optimisation et Simulation** (MOSIM 20) (author - speaker) – Agadir, Maroc – Oral presentation – *L'humain dans les systèmes de production basés sur les paradigmes IoT et CPS: état des lieux et perspectives* – Valette Etienne, Bril El-Haouzi Hind and Demesure Guillaume

2021 – **17th IFAC Symposium on Information Control Problems in Manufacturing** (INCOM 21) (co-author) – Budapest, Hongrie – Oral presentation, publication in proceedings – *Human system integration as a key approach to design manufacturing control system for Industry 4.0: Challenges, barriers, and opportunities.* – Bril El-Haouzi Hind and Valette Etienne

International journals with peer review

2021 – **Computers In Industry** (author) – *Formal and modelling frameworks for social holonic control architectures* – Valette Etienne, Bril El-Haouzi Hind, Demesure Guillaume and Pannequin Rémi

2021 – **Societies** (co-author) – *Social Dimensions in CPS & IoT Based Automated Production Systems* – Bril El-Haouzi Hind, Valette Etienne, Krings Bettina and António Brandão Moniz

Forthcoming – (author) – *Human in IoT and CPS based industrial systems: A Systematic Literature Review* – Valette Etienne, Bril El-Haouzi Hind and Demesure Guillaume

Synthèse en Français

1 Contexte et problématique

Au cours des 20 dernières années, les travaux du CRAN ont développé le concept de "*Système Contrôlé par le Produit*" (ou SCP) pour répondre à des problématiques industrielles de contrôle / synchronisation des flux physiques et informationels. La croissance et la complexification des systèmes manufacturiers, ainsi que l'évolution des modes de consommation ont montré les limites des systèmes décisionnels / de contrôle centralisés traditionnels. Dans ce contexte, l'approche SCP avait pour objectif de dépasser ces limites en favorisant une interopérabilité via le produit des systèmes centralisés / décentralisés. Elle a notamment été développée à travers le paradigme holonique (systèmes manufacturiers et systèmes de contrôles holoniques - HMS et HMC) dans le cadre du programme Systèmes Intelligents de Production (Intelligent Manufacturing Systems - IMS). On note en revanche un certain manque de généricité et de formalisme dans cette recherche, principalement axée sur l'apport de solutions concrètes à des systèmes industriels spécifiques.

A travers l'étude des travaux successifs constituant ce socle scientifique et technologique, la nécessité de prendre en compte le facteur humain dans le développement des architectures de contrôle a largement pu être établie. Toutefois, il apparait également que cette prise en compte est rarement effective lors de la conception des architectures de contrôle, proposant généralement des solutions techno-centrées, même pour répondre à des besoins de type managériaux. Ainsi, l'humain n'est intégré à la boucle de contrôle qu'*a posteriori*, avec la mission de garantir le fonctionnement et les performances du système en tout temps, et plus particulièrement lorsque celui-ci est perturbé. Cette approche a pour principaux inconvénients d'amener le travailleur à un niveau d'attention très faible, dû à un travail routinier, lorsque le système fonctionne sans problème (et donc à une faible réactivité), et à l'inverse de provoquer des surcharges cognitives, voire même physiques, lorsque le système est perturbé.

Parallèlement, la montée en puissance de la 4$^{\text{ème}}$ révolution industrielle a pu être observée, notamment à travers la création de nombre d'initiatives nationales telles que l'Industie 4.0 en Allemagne ou l'Industrie du futur en France. Au delà d'un cadre technologique visant à la modernisation des parcs industriels grâces aux dernières innovations, l'objectif de ces initiatives est de revenir sur des problématiques plus centrées humain, sociales, et sociétales. C'est d'ailleurs en partie a l'occultation de ces aspects par les révolutions industrielles précédentes, focalisées sur l'automatisation et l'intégration informatique massive des systèmes, que peut être imputée le manque de prise en compte du facteur humain précédemment décrit. L'importance de cette dimension est d'ailleurs soulignée par l'émergence de l'*Industrie 5.0* depuis quelques années, et abordée par la Commission Européenne comme une politique à part entière depuis 2020. Alors que l'Industrie 4.0 semble principalement tournée vers le développement technologique, en particulier des Systèmes Cyber-Physiques ("Cyber-Physical Systems" en Anglais, ou CPS) et de l'Internet des Objets ("Internet of Things" en Anglais, ou IoT), les aspects sociaux et économiques peuvent être perçus comme "manqués" ou "délaissés". L'Industrie 5.0 s'intéresse donc à les ramener sur le devant de la scène scientifique, tout en s'appuyant sur les développements technologiques de l'Industrie 4.0.

Ces diverses observations, s'appuyant sur une étude préliminaire de la littérature, ont permis de dégager les deux questions de recherche suivantes: [QR1] *Comment tirer parti des concepts introduits par l'Industrie 4.0, tels que l'Internet des Objets et les Systèmes Cyber-Physiques, pour le développement des architectures de contrôle des systèmes manufacturiers ?* [QR2] *Comment faciliter l'intégration de l'humain au sein des systèmes manufacturiers de demain, complexes, adaptables, et socio-techniques ?* L'hypothèse de travail considérée dans cette thèse est donc que l'établissement d'un cadre de référence pour la conception et la mise en oeuvre des architectures de contrôle des systèmes industriels y faciliterait l'intégration du facteur humain.

2 Etat de l'art

Pour répondre aux questions de recherche précédemment énoncées, ce chapitre propose une revue systématique de la litérature questionnant, dans un premier temps, les considérations humaines et sociales dans les développements technologiques liés aux paradigmes Industries 4.0 et 5.0. Notamment, l'interêt a initialement été porté sur les notions de CPS et d'IoT. Bien que ces deux termes puissent être dans une certaine mesure confondus dans la litérature, ils sont expressément distingués dans cette étude. L'IoT est un concept qui remonte au début des années 2000. Il s'appuie sur des technologies de type TCP/IP pour créer une synchronisation / connectivité horizontale entre des objets physiques ou des objets numériques. De son côté, la notion de CPS a été énoncée en 2006, et désigne une synchronisation / connectivité verticale établie entre des objets physiques et leurs jumeaux numériques grâce à des technologies telles que l'infonuagique ou les capteurs.

Pilliers de l'Industrie 4.0 et des initiatives nationales y faisant écho, ces deux concepts ont connu un important succès au cours des dernières années. Ainsi, nombre de variantes et dérivés ont vu le jour, notamment dans le cadre d'approches sociales et centrées-Homme. L'étude de la litérature a par ailleurs permis d'identifier plus d'une dizaine de ces approches, mettant en oeuvre 3 types de sociabilités bien distincts. Le premier met en oeuvre une sociabilité basée sur des interfaces de communiation de type *peer-to-peer*, où toute interaction entre 2 agents peut être considérée comme sociale. Dans le cas du second, la sociabilité est établie en structurant les échanges de données entre les différents agents d'un système sur la base des architectures de services de réseaux sociaux (tels que Facebook, Instagram, ou Twitter). Le troisième et dernier type de sociabilité identifié ici consiste en une transposition de relations sociales, semblables à celles observables au sein des sociétés humaines dans le cadre de travaux anthropologiques (anthroposociales), à un système d'agents pour le structurer. Qui plus est, il a également été établi que ces 3 sociabilités supportent l'existence des 4 types de systèmes socio-techniques suivants: 1) systèmes techniques d'objets communicants, 2) systèmes techniques interagissant avec les humains, 3) réseaux sociaux d'objets communicants, et 4) réseaux sociaux d'agents socio-techniques. Ces 3 modes de sociabilité ainsi que ces 4 types de systèmes socio-techniques se retrouvent par ailleurs dans les cadres d'analyse à travers lesquels a été étudiée la litérature.

La première analyse s'est penchée sur l'étude de la nature des systèmes présents dans la litérature liée aux CPS et à l'IoT. Pour ce faire, un cadre systémique basé sur les 4 pilliers de cette dernière discipline a été établi. Ces derniers reposent sur les notions d'*Interaction / Interrelation*, d'*Integralité*, d'*Organisation*, et de *Complexité*. Le premier pôle, axé sur l'étude des *interactions* et *interrelation*, s'intéresse aux relations s'établissant au sein d'un système entre ses éléments pris deux à deux (influence, échanges de matière, d'énergie, d'informations, etc.). Cette notion fait donc, dans le cas de cette étude, directement écho aux 3 modes de sociabilité présentés précédement. Le second pôle, axé sur l'étude de l'*intégralité* des systèmes, s'intéresse à la fois à l'interdépendence des élements d'un système et à sa cohérence globale. Ce pôle correspond à une approche plus globale du système, ne prenant plus ses éléments deux à deux, mais en temps qu'ensemble cohérent. Il est donc ici associé aux 4 types de systèmes socio-techniques identifiés, mettant en oeuvre de manière globale les 3 modes de sociabilité. Le troisième pôle s'intéresse à l'étude de l'*organisation* des systèmes, c'est à dire à la manière dont leurs éléments sont organisés pour atteindre leurs objectifs. Ce pôle fait donc référence à l'organisation structurelle et fonctionnelle des élements d'un système, ce qui est associé ici à la nature *hierarchique*, *hétérarchique*, ou *isoarchique* des architectures de contrôles y étant mises en places. Le quatrième et dernier pôle est axé sur l'étude de la *complexité* des systèmes, i.e., la propension de comportements non-linéaires à émerger spontanément au sein de ces derniers, avec des effets parfois positifs, et parfois négatifs. Cette notion est au fondement de l'approche systémique dans l'étude des systèmes complexes, motivée par les limites des méthodes analytiques classiques. Cette analyse systémique a pu montrer que la majorité des approches et systèmes proposés dans la litérature, bien que mettant en avant leurs aspects "centrés-Homme" et "sociaux", faisaient une nette distinction entre système technique et facteur humain. Au final, seuls quelques travaux proposent une vision ou les interactions entre les agents d'un système seraient considérés comme une extension / projection inclusive des relations sociales humaines au reste du système. Ainsi, les développements proposés dans ces travaux relèvent plus des systèmes techniques que des systèmes socio-techniques à proprement parler.

La seconde analyse s'est donc portée sur la contribution de ces développements techniques à l'intégration du facteur humain dans les systèmes industriels. Il est vite apparu que cette analyse rejoignait le cadre d'étude proposé par la commission européenne pour la vision Industrie 5.0 énoncée précédemment. Ce cadre d'étude classifie les technologies habilitantes de l'Industrie 5.0 en 6 pôles distincts, ayant été ici utilisés pour analyser la litérature: 1) *solutions centrées-Homme & interaction Homme-machine*, 2) *technologies bio-inspirées & matériaux intelligents*, 3) *jumeaux numériques & simulation en temps réel*, 4) *cybersécurité pour la transmission, le stockage et l'analyse de données*, 5) *Intelligence Artificielle*, et 6) *efficacité énergétique et fiabilité de l'autonomie*. L'étude de la litérature liée aux notions de CPS et d'IoT à travers le cadre de référence proposé par l'Industrie 5.0 tend à montrer que les notions d'efficacité énergétique, d'Intelligence Artificielle, ou de matériaux intelligents y sont peu présentes, ces dernières étant au coeur de domaines de recherche spécifiques. En revanche, les notions d'interactions Homme-machines, de jumeaux numériques ou de cybersécurité sont extrêmement présentes. D'une part, l'accent y est mis sur l'amélioration de la prise en compte du facteur humain au sein des systèmes par une meilleur prise en compte de ce dernier, et notamment de ses facteurs physiques et cognitifs (rendre le système plus résilient à la variabilité humaine). D'autre part, la notion d'acceptabilité humain / système apparaît comme centrale dans la recherche, et plus particulièrement à travers la notion de *tangibilité*. Cette tangibilité peut être permise par le biais de technologies de réalité virtuelle, augmentée, ou mixte, mais également par la proposition de système d'aide à la prise de décisions plus facilement compréhensibles par l'opérateur. On peut notemment citer à ce titre le développement de l'Intelligence Artificielle causale, visant à proposer des modèles basés sur des relations cause-conséquence, sensés être plus explicables et accessible que les modèles d' Intelligence Artificielle actuels basés sur des corrélations.

L'étude de cette littérature concernant les aspects humains et sociaux à travers les paradigmes IoT et CPS pour le développement de l'industrie de demain a pu montrer l'intérêt croissant du sujet dans le cadre d'une recherche très internationale, bien qu'une certaine absence de vision globale ait pu être constatée. Toutefois, nul doute que les technologies habilitantes identifiées ici faciliteront l'integration du facteur humain dans les systèmes socio-techniques complexes (tels que les sytèmes manufacturiers). Ces technologies crédibilisent ainsi le concept de conception centrée-Homme, et constituent un vecteur d'acceptabilité pour les futurs systèmes basés sur l'IoT, les CPS, et leurs évolutions. La convergence de ces technologies pour l'intégration Humain-Système (*Human-System Integration* en Anglais, ou *HSI*) constitue par ailleurs aujourd'hui un domaine de recherche à part entière. Cependant, ce domaine semble s'intéresser assez peu à la formalisation de la structure des systèmes et de leurs architectures. Ainsi, en s'appuyant sur les différentes approches humaines et sociales trouvées dans la litérature relative aux notions de CPS et d'IoT, et dans l'idée d'améliorer l'acceptabilité, et donc l'integration, humain-système, ce travail de thèse propose d'établir un cadre de conception pour les architectures de contrôle holoniques, basé sur une définition sociale et formelle des relations liant les éléments d'un système deux à deux.

3 Proposition d'un modèle formel

Ce chapitre propose une approche sociale pour la modélisation des architectures de contrôle holoniques. Les architectures de contrôle sont traditionnellement décrites à travers les 4 concepts de *composants*, *structure*, *comportement*, et *dynamique*. La notion de *composant* élémentaire d'une architecture est ici associée à celle de *holon*, dont la définition est abordée dans ce travail à travers le prisme de la théorie du contrôle. Il s'agit d'un élément cyber-physique du système, à la structure récursive, combinant les aspects opérationels et décisionels habituellement distingués en théorie du contrôle. Ce holon peut décrire un objet ou un agent qu'il soit naturel ou artefactuel, humain ou non. La notion de *structure* d'une architecture de contrôle fait référence à la manière dont ses composants sont arrangés entre eux, c'est à dire aux relations qui les lient. Traditionnellement, les architectures sont caractérisées de hierarchiques, hétérarchiques, ou isoarchiques, en évaluant les relations ayant trait à la notion de supériorité / subordination entre leurs holons pris deux à deux. L'approche sociale proposée ici vise à étoffer ce panel grâce à l'identification et à la formalisation d'autres types de relations sociales, inspirées de travaux anthropologiques. La notion de *comportement* d'un système de contrôle est relative à son processus décisionnel. Ce dernier se base sur un ensemble de critères, de contraintes, et d'objectifs alimentant des méthodes et algorithmes de différentes natures (réactifs, prédictifs, mixtes, etc.). L'utilisation de 3 modes de contrôle différents (i.e.: comportements) dans l'instanciation du modèle social permet d'intégrer cet aspect à l'étude. Enfin, la notion de *dynamique* fait référence aux étapes de régulation, adaptation structurelle et fonctionnelle, et évolution, entreprises par le système pour garantir son équilibre. Cet aspect n'est pas particulièrement développé en tant que tel dans ces travaux de thèse, mais reste présent lorsque l'on considère l'aspect dynamique de l'établissement et de la disparition des relations sociales entre holons au sein du système.

La contribution principale repose ici dans la proposition d'une modélisation formelle pour une typologie de relations sociales élémentaires. Ces relations anthropo-sociales élémentaires sont au nombre de 4, et lient directement les holons d'un système deux à deux : on les appelle *Relations Directes*. Celles-ci traduisent des relations de parenté (Parental Relationship – PR), de propriété (Ownership Relationship – OR), de dépendence (Dépendency Relationship – DR), et de hierarchie (Hierarchical Relationship – DR). Ces relations sont orientées, c'est à dire que, dans le cadre d'une relation de hierarchie par exemple, qu'un holon i soit supérieur à holon j implique que le holon j soit subordonné au holon i. A priori, le holon j ne sera pas supérieur au holon i, sauf si une seconde relation de hierarchie, définie comme telle, est établie entre eux. Sur la base de ces 4 relations directes, 16 relations émergentes peuvent être établies : ces relations lient ensemble deux holons travers les relations que ces derniers peuvent avoir avec un $3^{\text{ème}}$ holon commun. Les relations émergentes liant deux holons à un même $3^{\text{ème}}$ via des relations directes de nature différentes sont simplement appelée "Relations de Contact Social" (Social Contact Relationship – SCR), et n'ont pour l'instant pas été approfondies dans ces travaux. Qui plus est, une distinction supplémentaire est faite entre celles liant deux holons à un même $3^{\text{ème}}$ via des relations directes de même nature. D'une part, elles sont caractérisées de *transitives* si deux holons ont une même relation directe, avec une orientation opposée, avec un même $3^{\text{ème}}$: par transitivité, cette relation émergente entre les 2 holons est assimilée à une relation directe. D'autre part, elles sont caractérisées de *symétriques* si deux holons ont une même relation directe, avec une même orientation, avec un même $3^{\text{ème}}$. Par symétrie, ces deux holons seront liés par une relation émergente réciproque. Ces 4 relations émergentes symétriques expriment ainsi une co-parenté (Co-Parental Relationship – C-PR), une co-propriété (Co-Ownership Relationship – C-OR), une co-dépendence (Co-Dependency Relationship – C-DR), ou une co-hierarchie (Co-Hierarchical Relationship – C-HR) entre 2 holons.

Après avoir établi et formellement défini la typologie des relations structurant la holarchie sociale proposée par ces travaux, la dernière section de ce chapitre porte sur leur cadre d'instanciation. Cette instanciation est réalisée sur la base d'un système de type multi-agents, motivant l'emploi du langage de modélisation UML pour la conception des agents et leurs interactions. La première étape consiste en la définition et la modélisation UML des holons et relations constituant le système. Différents profils ont ainsi été établis pour chacun des types de holons susceptibles d'être présents au sein du système d'étude. Les activités d'établissement / disparition des relations entre les agents ont été définies grâce à un ensemble de machines à états. Les différents évênements déclenchant ces machines à états ont eux été créés en utilisant le standard FIPA de la librairie Java Agent Development (Jade). Ces éléments constituent le cadre de modélisation du modèle. L'instanciation en elle-même est réalisée grâce à l'emploi de "fabriques" UML (ou factory), tandis que la visualisation de l'apparition / disparition des relations sociales au sein du système est permise par l'usage d'un agent espion (ou sniffer), enregistrant les évênements de type création / disparition de holons ainsi que les messages échangés entre eux. Ainsi, ce cadre logiciel permet la modélisation, l'instanciation, et la visualisation du modèle social formel proposé sur un système multi-agents concret.

4 Validation du modèle

Ce chapitre propose un exemple d'instanciation du modèle social proposé pour en établir la preuve de concept. En l'occurrence, le système d'étude est la plateforme TRACILOGIS du CRAN. La première partie du chapitre consiste en une présentation détaillée de la plateforme, de son architecture logicielle, de ses différents composants (agents utilitaires, holons ressources, produits, et interface), et de ses différents modes de contrôle (purement réactif, consensus, et négociation). 3 zones de la plateforme sont utilisées dans ces travaux: les zones A, B, et D. Dans l'ensemble, on considère le système comme étant composé d'holons produits subissant divers usinages et assemblages (resources de types "machines"), mais également des transformations de type routage (resources de type "aiguillages"). Les produits sont identifiés via des portiques RFID, associés à un holon RFID par zone. Egalement pour chacune des zones, un holon PLC est en charge du contrôle des actioneurs physiques. En ce qui concerne les modes de contrôles utilisés dans l'étude, ils sont tous trois basés sur une approche de type Système Controlé par le Produit. En configuration purement réactive, les holons produits ré-estiment leur route optimale à chaque passage de ressource grâce à un algorithme de Dijkstra, en se basant sur l'état actuel du système global (son état propre, celui des autres produits, celui des ressources). En configuration "consensus", à chaque passage d'aiguillage, un algorithme ré-évalue non seulement la route optimale du holon produit, mais également celle de tous les produits voisins afin d'obtenir une convergence optimale des dates de complétion garantissant les performances du système. En configuration "negociation", à chaque passage de resource, cette dernière établit un voisinage entre tous les produits devant y passer dans un futur proche et établit elle-même un ordre de priorité entre eux grace à un algorithme de type contrat-net. Ces deux approches (consensus et négociation) correspondent fonctionnellement à des extensions distinctes et disjointes du mode de pilotage purement réactif.

L'instanciation en elle-même n'a pas été réalisée sur le système physique de la plateforme, mais via une émulation de cette dernière pour des raisons de praticité. Pour chacun des trois modes de contôles énoncés précédement, des scénarios différents ont été appliqués. Grâce à l'outil logiciel de modélisation et visualisation développé pour les besoin de l'étude et présenté dans la section précédende, les créations et disparitions de relations sociales au sein du système en fonctionnement ont pu être visualisées sous forme de graphes. Cette expérimentation à pu permettre de démontrer l'applicabilité et l'expressivité du modèle social proposé. L'existance de deux types de relations a notamment pu être mise en lumière: certaines peuvent être caractérisées de sturcturelles, établies à l'initialisation du système pour la durée de son fonctionnement, tandis que d'autres peuvent être désignées de conjoncturelles (ou situationnelles) s'établissant de manière ponctuelle entre deux composants du système. Egalement, une certaine capacité d'agrégation du modèle a pu être observée: on observe 70 à 85% moins de relations crées qu'il n'y a de messages échangés entre les agents du système. Cela en rend l'étude plus aisée, le volume d'éléments à traiter étant plus faible, et une simple flèche étant plus aisément compréhensible qu'une sucession de lignes de messages en langage logiciel. Toutefois, cette instanciation n'a pas pu permettre d'étudier quantitativement la faculté du modèle à améliorer l'acceptabilité et l'intégration humain-système.

5 Conclusion

Ce dernier chapitre conclut le mémoire en revenant sur les points principaux développés au cours de ce travail de thèse, et déjà synthétisés ici. Il revient également sur la nécessité de tester plus avant la robustesse du modèle proposé, malgré l'établissement de la preuve de concept. Des notions complémentaires de *Degré* ou d'*Intensité* de relation pourront être développées, pour évaluer plus précisément la force d'une relation par exemple, ou pour en déterminer un seuil d'activation ou un niveau de criticité. La contribution et le potentiel de cette approche au développement d'architectures de contrôle pour les systèmes manufacturiers, qui y facilitent l'intégration du facteur humain, restent encore à évaluer plus précisément, bien qu'elle semble a priori déjà proposer quelques éléments dans ce sens (agrégation, visibilité, caractère social inspiré-

Homme). Qui plus est, des notions telles que l'intégration de facteurs physiques, physiologiques, psychologies, cognitifs ou sociétaux n'ont pas été particulièrement traitées ici. Cela pourra être envisagé à l'avenir, afin d'explorer de nouveaux modèles d'organisation pour les chaînes de production multimodales, qui soient reconfigurables, connectés, et offrant différents niveaux de coopération homme-machine.

Bibliography

[1] Acatech. Securing the future of German manufacturing industry: Recommendations for implementing the strategic initiative INDUSTRIE 4.0 - Final report of the Industrie 4.0 Working Group. Tech. rep., German Academy of Science and Engineering, Germany, Apr. 2013.

[2] Adam, E., and Mandiau, R. Roles and Hierarchy in Multi-agent Organizations. In *Multi-Agent Systems and Applications IV*, vol. 3690. Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 539–542. Series Title: Lecture Notes in Computer Science.

[3] Adam, E., Vergison, E., Kolski, C., and Mandiau, R. Holonic User Driven Methodologies and Tools for Simulating Human Organizations. In *Simulation In Industry* (Passau, Germany, Oct. 1997), Society for Computer Simulation, p. 7.

[4] Ajeev, A., Javaregowda, B. H., Ali, A., Modak, M., Patil, S., Khatua, S., Ramadoss, M., Kothavade, P. A., and Arulraj, A. K. Ultrahigh Sensitive Carbon-Based Conducting Rubbers for Flexible and Wearable Human–Machine Intelligence Sensing. *Advanced Materials Technologies 5*, 12 (2020), 2000690. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/admt.202000690.

[5] Alam, T. A Reliable Communication Framework and its Use in Internet of Things (Iot). SSRN Scholarly Paper ID 3619450, Social Science Research Network, Rochester, NY, May 2018.

[6] Aleem, S., Yang, P., Masood, S., Li, P., and Sheng, B. An accurate multi-modal biometric identification system for person identification via fusion of face and finger print. *World Wide Web 23*, 2 (Mar. 2020), 1299–1317.

[7] Alford, W. A., Kawamura, K., and Wilkes, D. M. Human-directed local autonomy for motion guidance and coordination in an intelligent manufacturing system. In *Architectures, Networks, and Intelligent Systems for Manufacturing Integration* (Pittsburgh, PA, Dec. 1997), B. Gopalakrishnan, S. Murugesan, O. Struger, and G. Zeichen, Eds., pp. 81–86.

[8] Almutairi, A., Wheeler, J. P., Slutzky, D. L., and Lambert, J. H. Integrating Stakeholder Mapping and Risk Scenarios to Improve Resilience of Cyber-Physical-Social Networks. *Risk Analysis 39*, 9 (2019), 2093–2112. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/risa.13292.

[9] Ansari, F., Hold, P., and Khobreh, M. A knowledge-based approach for representing jobholder profile toward optimal human–machine collaboration in cyber physical production systems. *CIRP Journal of Manufacturing Science and Technology 28* (Jan. 2020), 87–106.

[10] Ansari, F., Khobreh, M., Seidenberg, U., and Sihn, W. A problem-solving ontology for human-centered cyber physical production systems. *CIRP Journal of Manufacturing Science and Technology 22* (Aug. 2018), 91–106.

[11] Aoudia, H. *Perfect QRQC vol. 2-Prévention, standardisation, coaching: Le management qualité basé sur l'attitude San Gen Shugi.* Maxima, 2015.

[12] Ardanza, A., Moreno, A., Segura, A., de la Cruz, M., and Aguinaga, D. Sustainable and flexible industrial human machine interfaces to support adaptable applications in the Industry 4.0 paradigm. *International Journal of Production Research 57*, 12 (June 2019), 4045–4059. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/00207543.2019.1572932.

[13] Ashton, K. That 'Internet of Things' Thing, 2009.

[14] Atzori, L., Iera, A., and Morabito, G. SIoT: Giving a Social Structure to the Internet of Things. *IEEE Communications Letters 15*, 11 (Nov. 2011), 1193–1195.

[15] Atzori, L., Iera, A., Morabito, G., and Nitti, M. The Social Internet of Things (SIoT) – When social networks meet the Internet of Things: Concept, architecture and network characterization. *Computer Networks 56*, 16 (Nov. 2012), 3594–3608.

[16] Bagheri, B., Yang, S., Kao, H.-A., and Lee, J. Cyber-physical Systems Architecture for Self-Aware Machines in Industry 4.0 Environment. *IFAC-PapersOnLine 48*, 3 (Jan. 2015), 1622–1627.

[17] Baïna, S. *INTEROPERABILITE DIRIGEE PAR LES MODELES: Une Approche Orientée Produit pour l'interopérabilité des systèmes d'entreprise.* PhD thesis, Université Henri Poincaré-Nancy I, 2006.

[18] Barbosa, J., Leitao, P., Adam, E., and Trentesaux, D. Dynamic self-organization in holonic multi-agent manufacturing systems: The ADACOR evolution. *Computers in Industry 66* (Jan. 2015), 99–111.

[19] Bertalanffy, L. v. *General System Theory: Foundations, Development, Applications.* G. Braziller, New York, 1968. Google-Books-ID: 5mVQAAAAMAAJ.

[20] Blaiszik, B. J., Kramer, S. L., Olugebefola, S. C., Moore, J. S., Sottos, N. R., and White, S. R. Self-healing polymers and composites. *Annual review of materials research 40* (2010), 179–211.

[21] Bobillier-Chaumon, M., and Dubois, M. Technology Acceptance and Acceptability in Organizations. *Le travail humain Vol. 72*, 4 (2009), 355–382. Publisher: P.U.F.

[22] Böhnlein, D., Schweiger, K., and Tuma, A. Multi-agent-based transport planning in the newspaper industry. *International Journal of Production Economics 131*, 1 (2011), 146–157.

[23] Bonci, A., Pirani, M., Carbonari, A., Naticchia, B., and Cucchiarelli, A. Holonic overlays in cyber-physical system of systems. In *International Conference on Emerging Technologies and Factory Automation (ETFA)* (2018), p. 4.

[24] Borangiu, T., Răileanu, S., Berger, T., and Trentesaux, D. Switching mode control strategy in manufacturing execution systems. *International Journal of Production Research 53*, 7 (2015), 1950–1963.

[25] BORDEL, B., ALCARRIA, R., ROBLES, T., AND MARTIN, D. Cyber–physical systems: Extending pervasive sensing from control theory to the Internet of Things. *Pervasive and Mobile Computing 40* (Sept. 2017), 156–184.

[26] BOY, G. Design for Safety: A Cognitive Engineering Approach. In *The Safety of Intelligent Driver Support Systems*, y. barnard, r. risser & j. krems ed. Ashgate, UK, 2011.

[27] BOY, G. A. *Human-Systems Integration Design: From Virtual to Tangible.* CRC Press, Feb. 2020.

[28] BOY, G. A., AND NARKEVICIUS, J. M. Unifying human centered design and systems engineering for human systems integration. In *Complex Systems Design & Management.* Springer, 2014, pp. 151–162.

[29] BRIL EL-HAOUZI, H. *Contribution à la conception et à l'évaluation des architectures de pilotage des systèmes de production adaptables : vers une approche anthropocentrée pour la simulation et le pilotage.* Habilitation à Diriger des Recherches (HDR), Université de Lorraine, 2017.

[30] BRIL EL-HAOUZI, H., AND VALETTE, E. Human System Integration As a Key Approach to Design Manufacturing Control System for Industry 4.0 : Challenges, Barriers, and Opportunities. In *17th IFAC Symposium on Information Control Problems in Manufacturing (INCOM)* (Budapest, Hungary, 2021), IFAC, p. 6.

[31] CABALLERO, V., VERNET, D., AND ZABALLOS, A. A Heuristic to Create Prosumer Community Groups in the Social Internet of Energy. *Sensors 20*, 13 (Jan. 2020), 3704. Number: 13 Publisher: Multidisciplinary Digital Publishing Institute.

[32] CAI, L., LIU, X., DING, H., AND CHEN, F. Human Action Recognition Using Improved Sparse Gaussian Process Latent Variable Model and Hidden Conditional Random Filed. *IEEE Access 6* (2018), 20047–20057. Conference Name: IEEE Access.

[33] CAO, H., YANG, X., AND DENG, R. Ontology-Based Holonic Event-Driven Architecture for Autonomous Networked Manufacturing Systems. *IEEE Transactions on Automation Science and Engineering 18*, 1 (Jan. 2021), 205–215. Conference Name: IEEE Transactions on Automation Science and Engineering.

[34] CARDIN, O., DERIGENT, W., AND TRENTESAUX, D. Evolution of holonic control architectures towards Industry 4.0: A short overview. In *16th IFAC Symposium on Information Control Problems in Manufacturing, INCOM 2018* (Bergamo, Italy, June 2018), vol. 51 of *IFAC-PapersOnLine*, pp. 1243–1248. Issue: 11.

[35] CARDIN, O., TRENTESAUX, D., THOMAS, A., CASTAGNA, P., BERGER, T., AND EL-HAOUZI, H. B. Coupling predictive scheduling and reactive control in manufacturing hybrid control architectures: state of the art and future challenges. *Journal of Intelligent Manufacturing 28*, 7 (2017), 1503–1517.

[36] CAUSALENS. Why Causal AI ? `https://www.causalens.com/why-causal-ai/`, 2021.

[37] CHEN, S., WANG, J., LI, H., WANG, Z., LIU, F., AND LI, S. Top-Down Human-Cyber-Physical Data Fusion Based on Reinforcement Learning. *IEEE Access 8* (2020), 134233–134245. Conference Name: IEEE Access.

[38] Chen, X., Eder, M. A., Shihavuddin, A., and Zheng, D. A Human-Cyber-Physical System toward Intelligent Wind Turbine Operation and Maintenance. *Sustainability 13*, 2 (Jan. 2021), 561. Number: 2 Publisher: Multidisciplinary Digital Publishing Institute.

[39] Chin, K. O., Gan, K. S., Alfred, R., and Lukose, D. Agent Architecture: An Overview. *December 2014 1*, 1 (2014), 18–35.

[40] Chung, K. C., and Liang, S. W.-J. An Empirical Study of Social Network Activities via Social Internet of Things (SIoT). *IEEE Access 8* (2020), 48652–48659. Conference Name: IEEE Access.

[41] Cimini, C., Pirola, F., Pinto, R., and Cavalieri, S. A human-in-the-loop manufacturing control architecture for the next generation of production systems. *Journal of Manufacturing Systems 54* (Jan. 2020), 258–271.

[42] Cox, J. S., and Durfee, E. H. Discovering and exploiting synergy between hierarchical planning agents. In *Proceedings of the second international joint conference on Autonomous agents and multiagent systems* (2003), pp. 281–288.

[43] De Rosnay, J. *Le macroscope. Vers une vision globale.* Média Diffusion, 2014.

[44] Demesure, G., El-Haouzi, H. B., and Iung, B. Mobile-agents based hybrid control architecture—implementation of consensus algorithm in hierarchical control mode. *CIRP Annals* (2021).

[45] Derigent, W., Cardin, O., and Trentesaux, D. Industry 4.0: contributions of holonic manufacturing control architectures and future challenges. *Journal of Intelligent Manufacturing* (Jan. 2020).

[46] Ding, K., and Jiang, P. Incorporating social sensors, cyber-physical system nodes, and smart products for personalized production in a social manufacturing environment. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 232*, 13 (Nov. 2018), 2323–2338. Publisher: IMECHE.

[47] Donnadieu, G., Durand, D., Neel, D., Nunez, E., and Saint-Paul, L. The Systemic Approach: what is it all about?, 2003.

[48] Dumetz, L. *Simulation combinée des processus de production et des processus de pilotage: Analyse comparative de stratégies de pilotage pour la production de bois d'oeuvre.* PhD thesis, Université Laval, 2018.

[49] El Haouzi, H. *Approche méthodologique pour l'intégration des systèmes contrôlés par le produit dans un environnement de juste-à-temps: Application à l'entreprise Trane.* PhD thesis, Université Henri Poincaré-Nancy I, 2008.

[50] El-Haouzi, H. B., Valette, E., Krings, B.-J., and Moniz, A. B. Social Dimensions in CPS & IoT Based Automated Production Systems. *Societies 11*, 3 (Sept. 2021), 98. Number: 3 Publisher: Multidisciplinary Digital Publishing Institute.

[51] Emmanouilidis, C., Pistofidis, P., Bertoncelj, L., Katsouros, V., Fournaris, A., Koulamas, C., and Ruiz-Carcel, C. Enabling the human in the loop: Linked data and knowledge in industrial cyber-physical systems. *Annual Reviews in Control 47* (Jan. 2019), 249–265.

[52] Esmaeili, A., Mozayani, N., Jahed Motlagh, M. R., and Matson, E. T. A socially-based distributed self-organizing algorithm for holonic multi-agent systems: Case study in a task environment. *Cognitive Systems Research 43* (June 2017), 21–44.

[53] European Commission. *Enabling Technologies for Industry 5.0: results of a workshop with Europe's technology leaders.* Publications Office of the European Union, LU, 2020.

[54] European Commission. PERFoRM - Production harmonizEd Reconfiguration of Flexible Robots and Machinery. Horizon 2020. http://www.horizon2020-perform.eu/index.php?action=project. Page consultée le 24 juillet 2020, 2020.

[55] European Commission. *Industry 5.0: towards a sustainable, human centric and resilient European industry.* Publications Office of the European Union, LU, 2021.

[56] Fadil, A., Trentesaux, D., and Branger, G. Event management architecture for the monitoring and diagnosis of a fleet of trains: a case study. *Journal of Modern Transportation 27*, 3 (Sept. 2019), 169–187.

[57] Fantini, P., Pinzone, M., and Taisch, M. Placing the operator at the centre of Industry 4.0 design: Modelling and assessing human activities within cyber-physical systems. *Computers & Industrial Engineering 139* (Jan. 2020), 105058.

[58] Ferber, J. *Multiagent Systems, an Introduction to Distributed Artificial Intelligence.* Pearson Education, 2005. Pages: 528.

[59] Fiske, A. P. The Four Elementary Forms of Sociality: Framework for a Unified Theory of Social Relations. *Psychological Review 99*, 4 (Oct. 1992), 689–723.

[60] FOUNDATION FOR INTELLIGENT PHYSICAL AGENTS. FIPA Agent Management Specification, Oct. 2001.

[61] Fox, S., and Kotelba, A. Variational Principle of Least Psychomotor Action: Modelling Effects on Action from Disturbances in Psychomotor Work Involving Human, Cyborg, and Robot Workers. *Entropy 21*, 6 (June 2019), 543. Number: 6 Publisher: Multidisciplinary Digital Publishing Institute.

[62] Gamboa Quintanilla, F., Cardin, O., L'Anton, A., and Castagna, P. A modeling framework for manufacturing services in Service-oriented Holonic Manufacturing Systems. *Engineering Applications of Artificial Intelligence 55* (Oct. 2016), 26–36.

[63] Garrido-Hidalgo, C., Hortelano, D., Roda-Sanchez, L., Olivares, T., Ruiz, M. C., and Lopez, V. IoT Heterogeneous Mesh Network Deployment for Human-in-the-Loop Challenges Towards a Social and Sustainable Industry 4.0. *IEEE Access 6* (2018), 28417–28437. Conference Name: IEEE Access.

[64] Gershenfeld, N., Krikorian, R., and Cohen, D. The Internet of Things. *Scientific American 291*, 4 (2004), 76–81.

[65] Gill, K. S. Holons on the Horizon: Re-Understanding Automation and Control. *IFAC-PapersOnLine 52*, 25 (2019), 556–561.

[66] Giovannini, A. *A knowledge representation framework for the design ant the evaluation of a product variety.* PhD thesis, Université de Lorraine, 2015.

[67] Gouyon, D. *Contrôle par le produit des systèmes d'exécution de la production: apport des techniques de synthèse.* PhD thesis, Université Henri Poincaré-Nancy 1, 2004.

[68] Gualtieri, L., Palomba, I., Merati, F. A., Rauch, E., and Vidoni, R. Design of Human-Centered Collaborative Assembly Workstations for the Improvement of Operators' Physical Ergonomics and Production Efficiency: A Case Study. *Sustainability 12*, 9 (Jan. 2020), 3606. Number: 9 Publisher: Multidisciplinary Digital Publishing Institute.

[69] Guinard, D., Fischer, M., and Trifa, V. Sharing using social networks in a composable Web of Things. In *2010 8th IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops)* (Mannheim, Germany, Mar. 2010), IEEE, pp. 702–707.

[70] Gulati, N., and Kaur, P. D. Towards socially enabled internet of industrial things: Architecture, semantic model and relationship management. *Ad Hoc Networks 91* (Aug. 2019), 101869.

[71] Haavik, T. K. Keep your coats on: augmented reality and sensework in surgery and surgical telemedicine. *Cognition, Technology & Work 18*, 1 (Feb. 2016), 175–191.

[72] Hatvany, J., and Nemes, L. Intelligent Manufacturing Systems— A Tentative Forecast. *IFAC Proceedings Volumes 11*, 1 (1978), 895–899.

[73] Heragu, S. S., Graves, R. J., Kim, B.-I., and St Onge, A. Intelligent agent based framework for manufacturing systems control. *IEEE transactions on systems, man, and cybernetics-PART A: Systems and humans 32*, 5 (2002), 560–573.

[74] Herrera, C. *Cadre générique de planification logistique dans un contexte de décisions centralisées et distribuées.* PhD thesis, Université Henri Poincaré-Nancy 1, 2011.

[75] Hoc, J.-M., and Lemoine, M.-P. Cognitive Evaluation of Human-Human and Human-Machine Cooperation Modes in Air Traffic Control. *The International Journal of Aviation Psychology 8*, 1 (Jan. 1998), 1–32. Publisher: Taylor & Francis _eprint: https://doi.org/10.1207/s15327108ijap0801_1.

[76] Hsieh, F.-S. Collaborative workflow management in holonic multi-agent systems. In *KES International Symposium on Agent and Multi-Agent Systems: Technologies and Applications* (2011), Springer, pp. 383–393.

[77] Indriago, C., Cardin, O., Rakoto, N., Castagna, P., and Chacon, E. H2CM: A holonic architecture for flexible hybrid control systems. *Computers in Industry 77* (Apr. 2016), 15–28.

[78] Islam, S. O. B., Lughmani, W. A., Qureshi, W. S., Khalid, A., Mariscal, M. A., and Garcia-Herrero, S. Exploiting visual cues for safe and flexible cyber-physical production systems. *Advances in Mechanical Engineering 11*, 12 (Dec. 2019), 1687814019897228. Publisher: SAGE Publications.

[79] Jia, Y., Zhou, Z., Chen, F., Duan, P., Guo, Z., and Mumtaz, S. A Non-Intrusive Cyber Physical Social Sensing Solution to People Behavior Tracking: Mechanism, Prototype, and Field Experiments. *Sensors 17*, 1 (Jan. 2017), 143. Number: 1 Publisher: Multidisciplinary Digital Publishing Institute.

[80] Jiang, P., Ding, K., and Leng, J. Towards a cyber-physical-social-connected and service-oriented manufacturing paradigm: Social Manufacturing. *Manufacturing Letters 7* (Jan. 2016), 15–21.

[81] Jiang, P., Leng, J., Ding, K., Gu, P., and Koren, Y. Social manufacturing as a sustainable paradigm for mass individualization. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 230*, 10 (Oct. 2016), 1961–1968. Publisher: IMECHE.

[82] Jiao, J. R., Zhou, F., Gebraeel, N. Z., and Duffy, V. Towards augmenting cyber-physical-human collaborative cognition for human-automation interaction in complex manufacturing and operational environments. *International Journal of Production Research 58*, 16 (Aug. 2020), 5089–5111. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/00207543.2020.1722324.

[83] Jiménez, J.-F. *Dynamic and hybrid architecture for the optimal reconfiguration of control systems: application to manufacturing control.* PhD thesis, Université de Valenciennes et du Hainaut-Cambresis, 2017.

[84] Jimenez, J.-F., Bekrar, A., Zambrano-Rey, G., Trentesaux, D., and Leitao, P. Pollux: a dynamic hybrid control architecture for flexible job shop systems. *International Journal of Production Research 55*, 15 (Aug. 2017), 4229–4247.

[85] Jin-Lung Chirn, and McFarlane, D. A holonic component-based approach to reconfigurable manufacturing control architecture. In *Proceedings 11th International Workshop on Database and Expert Systems Applications* (London, UK, 2000), IEEE Comput. Soc, pp. 219–223.

[86] Karwowski, W. Ergonomics and human factors: the paradigms for science, engineering, design, technology and management of human-compatible systems. *Ergonomics 48*, 5 (2005), 436–463.

[87] Kim, J., and Park, E. Understanding social resistance to determine the future of Internet of Things (IoT) services. *Behaviour & Information Technology 0*, 0 (Oct. 2020), 1–11. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/0144929X.2020.1827033.

[88] Kitchenham, B. Procedures for Performing Systematic Reviews, 2004.

[89] Kitchenham, B., Pretorius, R., Budgen, D., Pearl Brereton, O., Turner, M., Niazi, M., and Linkman, S. Systematic literature reviews in software engineering – A tertiary study. *Information and Software Technology 52*, 8 (Aug. 2010), 792–805.

[90] Klein, T. *Le kanban actif pour assurer l'interopérabilité décisionnelle centralisé/distribué.* PhD thesis, Henry Pointcarré, Nancy, 2008.

[91] Koestler, A. *The Ghost In the machine.* Arkana Books, London, 1967.

[92] Koren, I., and Klamma, R. Enabling visual community learning analytics with Internet of Things devices. *Computers in Human Behavior 89* (Dec. 2018), 385–394.

[93] Kotak, D., Wu, S., Fleetwood, M., and Tamoto, H. Agent-based holonic design and operations environment for distributed manufacturing. *Computers in Industry 52*, 2 (Oct. 2003), 95–108.

[94] Kremer, R., and Norrie, D. Architecture and design of a Holonic Visual Interface. In *SMC 2000 CONFERENCE PROCEEDINGS: 2000 IEEE INTERNATIONAL CONFERENCE ON SYSTEMS, MAN & CYBERNETICS, VOL 1-5* (345 E 47TH ST, NEW YORK, NY 10017 USA, 2000), IEEE International Conference on Systems Man and Cybernetics Conference Proceedings, IEEE, pp. 1715–1720. Backup Publisher: IEEE Inc, Syst Man & Cybernet Soc ISSN: 1062-922X Type: Proceedings Paper.

[95] Le Moigne, J.-L. *Théorie du Système général.* PUF, Paris, 1977.

[96] Le Mortellec, A., Clarhaut, J., Sallez, Y., Berger, T., and Trentesaux, D. Embedded holonic fault diagnosis of complex transportation systems. *Engineering Applications of Artificial Intelligence 26*, 1 (Jan. 2013), 227–240.

[97] Lee, E. A. Cyber-Physical Systems - Are Computing Foundations Adequate? In *NSF Workshop On Cyber-Physical Systems: Research Motivation, Techniques and Roadmap* (Austin, TX, Oct. 2006), p. 10.

[98] Leitão, P. Holonic rationale and self-organization on design of complex evolvable systems. In *International Conference on Industrial Applications of Holonic and Multi-Agent Systems* (2009), Springer, pp. 1–12.

[99] Leitao, P., Colombo, A., and Restivo, F. ADACOR: A Collaborative Production Automation and Control Architecture. *IEEE Intelligent Systems 20*, 1 (Jan. 2005), 58–66.

[100] Leitao, P., and Restivo, F. ADACOR: A holonic architecture for agile and adaptive manufacturing control. *Computers in Industry 57*, 2 (Feb. 2006), 121–130.

[101] Leng, J., Jiang, P., Liu, C., and Wang, C. Contextual self-organizing of manufacturing process for mass individualization: a cyber-physical-social system approach. *Enterprise Information Systems 14*, 8 (Sept. 2020), 1124–1149. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/17517575.2018.1470259.

[102] Lesourne, J. *Les systèmes du destin.* Dalloz Economie, 1976.

[103] Leuvennink, J., Kruger, K., and Basson, A. Architectures for human worker integration in holonic manufacturing systems. In *International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing* (2018), Springer, pp. 133–144.

[104] Li, H., Palau, A. S., and Parlikad, A. K. A social network of collaborating industrial assets. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability 232*, 4 (Aug. 2018), 389–400. Publisher: SAGE Publications.

[105] Lin, C.-C., Deng, D.-J., and Jhong, S.-Y. A Triangular NodeTrix Visualization Interface for Overlapping Social Community Structures of Cyber-Physical-Social Systems in Smart Factories. *IEEE Transactions on Emerging Topics in Computing 8*, 1 (Jan. 2020), 58–68. Conference Name: IEEE Transactions on Emerging Topics in Computing.

[106] Liu, Q., Liu, Z., Xu, W., Tang, Q., Zhou, Z., and Pham, D. T. Human-robot collaboration in disassembly for sustainable manufacturing. *International Journal of Production Research 57*, 12 (June 2019), 4027–4044. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/00207543.2019.1578906.

[107] Liu, Z., Yang, D.-s., Wen, D., Zhang, W.-m., and Mao, W. Cyber-Physical-Social Systems for Command and Control. *IEEE Intelligent Systems 26*, 4 (July 2011), 92–96.

[108] Madakam, S., Ramaswamy, R., and Tripathi, S. Internet of Things (IoT): A Literature Review. *Journal of Computer and Communications 03*, 05 (2015), 164–173.

[109] Mala, D. J., and Sugumaran, V., Eds. *Integrating the Internet of Things Into Software Engineering Practices:*. Advances in Systems Analysis, Software Engineering, and High Performance Computing. IGI Global, 2019.

[110] Manceaux, A. *Contribution au rééquilibrage dynamique des lignes d'assemblage: modélisation, résolutions et applications*. PhD thesis, Université de Lorraine, 2015.

[111] Martin-Gomez, A., Avila-Gutierrez, M. J., and Aguayo-Gonzalez, F. Holonic Reengineering to Foster Sustainable Cyber-Physical Systems Design in Cognitive Manufacturing. *Applied Sciences 11*, 7 (Jan. 2021), 2941. Number: 7 Publisher: Multidisciplinary Digital Publishing Institute.

[112] Maturana, F., Shen, W., and Norrie, D. H. Metamorph: an adaptive agent-based architecture for intelligent manufacturing. *International Journal of Production Research 37*, 10 (1999), 2159–2173.

[113] Mayer, R. C., Davis, J. H., and Schoorman, F. D. An Integrative Model of Organizational Trust. *The Academy of Management Review 20*, 3 (July 1995), 709.

[114] McFarlane, D., Sarma, S., Chirn, J. L., Wong, C., and Ashton, K. The intelligent product in manufacturing control and management. *IFAC Proceedings Volumes 35*, 1 (2002), 49–54.

[115] Meng, C., Jiang, X. S., Wei, X. M., and Wei, T. A Time Convolutional Network Based Outlier Detection for Multidimensional Time Series in Cyber-Physical-Social Systems. *IEEE Access 8* (2020), 74933–74942. Conference Name: IEEE Access.

[116] Mezgebe, T. T. *Human-inspired algorithms for designing new control system in the context of factory of the future*. PhD thesis, Université de Lorraine, 2020.

[117] Mezgebe, T. T., and Bril El-Haouzi, H. Recursive hybrid control architecture to deal with reactivity in the context of industry 4.0. In *13ème Conférence Internationale de Modélisation, Optimisation et Simulation, MOSIM'20* (Agadir, Morocco, Nov. 2020).

[118] Mezgebe, T. T., Demesure, G., Bril El-Haouzi, H., Pannequin, R., and Thomas, A. CoMM: a consensus algorithm for multi-agent-based manufacturing system to deal with perturbation. *The International Journal of Advanced Manufacturing Technology 105*, 9 (Dec. 2019), 3911–3926.

[119] Mezgebe, T. T., El Haouzi, H. B., Demesure, G., Pannequin, R., and Thomas, A. Multi-agent systems negotiation to deal with dynamic scheduling in disturbed industrial context. *Journal of Intelligent Manufacturing 31*, 6 (2020), 1367–1382.

[120] Morel, G., Panetto, H., Zaremba, M., and Mayer, F. Manufacturing Enterprise Control and Management System Engineering: paradigms and open issues. *Annual Reviews in Control 27*, 2 (Jan. 2003), 199–209.

[121] Moulières-Seban, T., Bitonneau, D., Salotti, J.-M., Thibault, J.-F., and Claverie, B. Human Factors Issues for the Design of a Cobotic System. In *Advances in Human Factors in Robots and Unmanned Systems* (Cham, 2017), P. Savage-Knepshield and J. Chen, Eds., Advances in Intelligent Systems and Computing, Springer International Publishing, pp. 375–385.

[122] Müller, J. P., and Pischel, M. The agent architecture interrap: Concept and application. Tech. rep., Deutsches Forschungszentrum für Künstliche Intelligenz, 1993.

[123] Nikolakis, N., Alexopoulos, K., Xanthakis, E., and Chryssolouris, G. The digital twin implementation for linking the virtual representation of human-based production tasks to their physical counterpart in the factory-floor. *International Journal of Computer Integrated Manufacturing 32*, 1 (Jan. 2019), 1–12. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/0951192X.2018.1529430.

[124] Nikolakis, N., Maratos, V., and Makris, S. A cyber physical system (CPS) approach for safe human-robot collaboration in a shared workplace. *Robotics and Computer-Integrated Manufacturing 56* (Apr. 2019), 233–243.

[125] Ning, H., and Wang, Z. Future Internet of Things Architecture: Like Mankind Neural System or Social Organization Framework? *IEEE Communications Letters 15*, 4 (Apr. 2011), 461–463. Conference Name: IEEE Communications Letters.

[126] Ning, Z., Hu, X., Chen, Z., Zhou, M., Hu, B., Cheng, J., and Obaidat, M. S. A Cooperative Quality-Aware Service Access System for Social Internet of Vehicles. *IEEE Internet of Things Journal 5*, 4 (Aug. 2018), 2506–2517. Conference Name: IEEE Internet of Things Journal.

[127] Nitti, M., Girau, R., and Atzori, L. Trustworthiness Management in the Social Internet of Things. *IEEE Transactions on Knowledge and Data Engineering 26*, 5 (May 2014), 1253–1266.

[128] Nitti, M., Girau, R., Atzori, L., Iera, A., and Morabito, G. A subjective model for trustworthiness evaluation in the social Internet of Things. In *2012 IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC)* (Sydney, Australia, Sept. 2012), IEEE, pp. 18–23.

[129] Novas, J. M., Van Belle, J., Saint Germain, B., and Valckenaers, P. A collaborative framework between a scheduling system and a holonic manufacturing execution system. In *Service orientation in holonic and multi agent manufacturing and robotics*. Springer, 2013, pp. 3–17.

[130] Noyel, M. *Contrôle intégré du pilotage d'atelier et de la qualité des produits: application à la société ACTA mobilier*. PhD thesis, Université de Lorraine, 2015.

[131] Oliff, H., Liu, Y., Kumar, M., Williams, M., and Ryan, M. Reinforcement learning for facilitating human-robot-interaction in manufacturing. *Journal of Manufacturing Systems 56* (July 2020), 326–340.

[132] Ottaway, T., and Burns, J. An adaptive production control system utilizing agent technology. *International Journal of Production Research 38*, 4 (2000), 721–737.

[133] Ou-Yang, C., and Lin, J. The development of a hybrid hierarchical/heterarchical shop floor control system applying bidding method in job dispatching. *Robotics and Computer-Integrated Manufacturing 14*, 3 (1998), 199–217.

[134] Pach, C., Berger, T., Bonte, T., and Trentesaux, D. ORCA-FMS: a dynamic architecture for the optimized and reactive control of flexible manufacturing scheduling. *Computers in Industry 65*, 4 (May 2014), 706–720.

[135] Pannequin, R. *Proposition d'un environnement de modélisation et de test d'architectures de pilotage par le produit de systèmes de production.* PhD thesis, Université Henri Poincaré - Nancy 1, 2007.

[136] Pannequin, R., Morel, G., and Thomas, A. The performance of product-driven manufacturing control: An emulation-based benchmarking study. *Computers in Industry 60*, 3 (Apr. 2009), 195–203.

[137] Papetti, A., Gregori, F., Pandolfi, M., Peruzzini, M., and Germani, M. A method to improve workers' well-being toward human-centered connected factories. *Journal of Computational Design and Engineering 7*, 5 (Oct. 2020), 630–643.

[138] Parsons, T. Suggestions for a sociological approach to the theory of organizations-i. *Administrative science quarterly* (1956), 63–85.

[139] Parunak, H. V. D. Fractal actors for distributed manufacturing control. In *Proc. 2nd Conference on AI Applications* (1985), pp. 653–660.

[140] Parunak, H. V. D. Manufacturing experience with the contract net. *Distributed artificial intelligence 1* (1987), 285–310.

[141] Parunak, H. V. D., Baker, A. D., and Clark, S. J. The aaria agent architecture: An example of requirements-driven agent-based system design. In *Agents* (1997), pp. 482–483.

[142] Peruzzini, M., and Pellicciari, M. A framework to design a human-centred adaptive manufacturing system for aging workers. *Advanced Engineering Informatics 33* (Aug. 2017), 330–349.

[143] Peschke, J., Luder, A., and Kuhnle, H. The pabadis'promise architecture-a new approach for flexible manufacturing systems. In *2005 IEEE Conference on Emerging Technologies and Factory Automation* (2005), vol. 1, IEEE, pp. 6–pp.

[144] Pine II, J. B. *Mass Customization – The New Frontier in Business Competition*, harvard business school press ed. Harvard Business Review Press, 1992.

[145] Pintus, A., Carboni, D., Serra, A., and Manchinu, A. Humanizing the Internet of Things - Toward a Human-centered Internet-and-web of Things:. In *Proceedings of the 11th International Conference on Web Information Systems and Technologies* (Lisbon, Portugal, 2015), SCITEPRESS - Science and and Technology Publications, pp. 498–503.

[146] Pirvu, B.-C., Zamfirescu, C.-B., and Gorecky, D. Engineering insights from an anthropocentric cyber-physical system: A case study for an assembly station. *Mechatronics 34* (Mar. 2016), 147–159.

[147] Pokam, R., Debernard, S., Chauvin, C., and Langlois, S. Principles of transparency for autonomous vehicles: first results of an experiment with an augmented reality human–machine interface. *Cognition, Technology & Work 21*, 4 (Nov. 2019), 643–656.

[148] Pujo, P., Broissin, N., and Ounnar, F. PROSIS: An isoarchic structure for HMS control. *Engineering Applications of Artificial Intelligence 22*, 7 (Oct. 2009), 1034–1045.

[149] Pujol, J. M., Sanguesa, R., and Delgado, J. Extracting reputation in multi agent systems by means of social network topology. In *Proceedings of the first international joint conference on Autonomous agents and multiagent systems: part 1* (New York, NY, USA, July 2002), AAMAS '02, Association for Computing Machinery, pp. 467–474.

[150] Qasim, I., Anwar, M. W., Azam, F., Tufail, H., Butt, W. H., and Zafar, M. N. A Model-Driven Mobile HMI Framework (MMHF) for Industrial Control Systems. *IEEE Access 8* (2020), 10827–10846. Conference Name: IEEE Access.

[151] Raileanu, S., Parlea, M., Borangiu, T., and Stocklosa, O. A jade environment for product driven automation of holonic manufacturing. In *Service orientation in holonic and multi-agent manufacturing control*. Springer, 2012, pp. 265–277.

[152] Reason, J. *Human Error*. Cambridge University Press, Oct. 1990. Google-Books-ID: MdcLAQAAQBAJ.

[153] Reports, I. I. Internet of Things. Tech. rep., International Telecommunication Union (ITU), Geneva, Geneva, Nov. 2005.

[154] Rolón, M., and Martínez, E. Agent-based modeling and simulation of an autonomic manufacturing execution system. *Computers in industry 63*, 1 (2012), 53–78.

[155] Romero, D., Bernus, P., Noran, O., Stahre, J., and Fast-Berglund, A. The Operator 4.0: Human Cyber-Physical Systems & Adaptive Automation Towards Human-Automation Symbiosis Work Systems. In *Advances in Production Management Systems. Initiatives for a Sustainable World* (Cham, 2016), I. Naas, O. Vendrametto, J. Mendes Reis, R. F. Goncalves, M. T. Silva, G. von Cieminski, and D. Kiritsis, Eds., IFIP Advances in Information and Communication Technology, Springer International Publishing, pp. 677–686.

[156] Rüssmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., and Harnisch, M. Industry 4.0: The future of productivity and growth in manufacturing industries. *Boston Consulting Group 9*, 1 (2015), 54–89.

[157] Ruta, M., Scioscia, F., Loseto, G., and Sciascio, E. D. A Semantic-Enabled Social Network of Devices for Building Automation. *IEEE Transactions on Industrial Informatics 13*, 6 (Dec. 2017), 3379–3388. Conference Name: IEEE Transactions on Industrial Informatics.

[158] Ryu, K., and Jung, M. Agent-based fractal architecture and modelling for developing distributed manufacturing systems. *International Journal of Production Research 41*, 17 (2003), 4233–4255.

[159] Sadik, A. R., and Urban, B. A Holonic Control System Design for a Human & Industrial Robot Cooperative Workcell. In *2016 International Conference on Autonomous Robot Systems and Competitions (ICARSC)* (Bragança, Portugal, May 2016), IEEE, pp. 118–123.

[160] Salvador Palau, A., Liang, Z., Lutgehetmann, D., and Parlikad, A. K. Collaborative prognostics in Social Asset Networks. *Future Generation Computer Systems 92* (Mar. 2019), 987–995.

[161] Sanin, C., Haoxi, Z., Shafiq, I., Waris, M. M., Silva de Oliveira, C., and Szczerbicki, E. Experience based knowledge representation for Internet of Things and Cyber Physical Systems with case studies. *Future Generation Computer Systems 92* (Mar. 2019), 604–616.

[162] Schirner, G., Erdogmus, D., Chowdhury, K., and Padir, T. The future of human-in-the-loop cyber-physical systems. *Computer 46*, 1 (2013), 36–45.

[163] Segura, A., Diez, H. V., Barandiaran, I., Arbelaiz, A., Alvarez, H., Simoes, B., Posada, J., Garcia-Alonso, A., and Ugarte, R. Visual computing technologies to support the Operator 4.0. *Computers & Industrial Engineering 139* (Jan. 2020), 105550.

[164] Senehi, M., and Kramer, T. R. A framework for control architectures. *International Journal of Computer Integrated Manufacturing 11*, 4 (1998), 347–363.

[165] Sgaier, S. K., Huang, V., and Charles, G. The Case for Causal AI, 2020.

[166] Shi, H., Yang, M., and Jiang, P. Social Production System: A Three-Layer Smart Framework for Implementing Autonomous Human-Machine Collaborations in a Shop Floor. *IEEE Access 9* (2021), 26696–26711. Conference Name: IEEE Access.

[167] Shi, X., and Zhuge, H. Cyber Physical Socio Ecology. *Concurrency and Computation: Practice and Experience 23*, 9 (June 2011), 972–984.

[168] Simeone, O. A Very Brief Introduction to Machine Learning With Applications to Communication Systems. *IEEE Transactions on Cognitive Communications and Networking 4*, 4 (Dec. 2018), 648–664. Conference Name: IEEE Transactions on Cognitive Communications and Networking.

[169] Simoes, B., De Amicis, R., Barandiaran, I., and Posada, J. Cross reality to enhance worker cognition in industrial assembly operations. *The International Journal of Advanced Manufacturing Technology 105*, 9 (Dec. 2019), 3965–3978.

[170] Simsek, B., and Albayrak, S. Living factory: back to koestler in holonic manufacturing. In *IEEE International Conference on Industrial Informatics, 2003. INDIN 2003. Proceedings.* (Banff, AB, Canada, 2003), IEEE, pp. 255–262.

[171] Sinha, A., Shrivastava, G., Kumar, P., and Gupta, D. A community-based hierarchical user authentication scheme for Industry 4.0. *Software: Practice and Experience n/a*, n/a (2020). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/spe.2832.

[172] Smith, R. G. The contract net protocol: High-level communication and control in a distributed problem solver. *IEEE Transactions on computers 29*, 12 (1980), 1104–1113.

[173] Sonehara, N., Suzuki, T., Kodate, A., Wakahara, T., Sakai, Y., Ichifuji, Y., Fujii, H., and Yoshii, H. Data-Driven Decision-Making in Cyber-Physical Integrated Society. *IEICE TRANSACTIONS on Information and Systems E102-D*, 9 (Sept. 2019), 1607–1616. Publisher: The Institute of Electronics, Information and Communication Engineers.

[174] Song, Z., Sun, Y., Wan, J., Huang, L., Xu, Y., and Hsu, C.-H. Exploring robustness management of social internet of things for customization manufacturing. *Future Generation Computer Systems 92* (Mar. 2019), 846–856.

[175] Sowe, S. K., Simmon, E., Zettsu, K., de Vaulx, F., and Bojanova, I. Cyber-Physical-Human Systems: Putting People in the Loop. *IT Professional 18*, 1 (Jan. 2016), 10–13.

[176] Sparrow, D. E., Kruger, K., and Basson, A. H. An architecture to facilitate the integration of human workers in Industry 4.0 environments. *International Journal of Production Research 0*, 0 (June 2021), 1–19. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/00207543.2021.1937747.

[177] Stelea, G. A., Popescu, V., Sandu, F., Jalal, L., Farina, M., and Murroni, M. From Things to Services: A Social IoT Approach for Tourist Service Management. *IEEE Access 8* (2020), 153578–153588. Conference Name: IEEE Access.

[178] Stern, H., and Becker, T. Concept and Evaluation of a Method for the Integration of Human Factors into Human-Oriented Work Design in Cyber-Physical Production Systems. *Sustainability 11*, 16 (Jan. 2019), 4508. Number: 16 Publisher: Multidisciplinary Digital Publishing Institute.

[179] Sun, H., and Venuvinod, P. K. The human side of holonic manufacturing systems. *Technovation 21*, 6 (June 2001), 353–360.

[180] Sun, S., Zheng, X., Gong, B., García Paredes, J., and Ordieres-Meré, J. Healthy Operator 4.0: A Human Cyber–Physical System Architecture for Smart Workplaces. *Sensors 20*, 7 (Jan. 2020), 2011. Number: 7 Publisher: Multidisciplinary Digital Publishing Institute.

[181] Takabayashi, K., Tanaka, H., and Sakakibara, K. Toward an Advanced Human Monitoring System Based on a Smart Body Area Network for Industry Use. *Electronics 10*, 6 (Jan. 2021), 688. Number: 6 Publisher: Multidisciplinary Digital Publishing Institute.

[182] Tang, D., Gu, W., Wang, L., and Zheng, K. A neuroendocrine-inspired approach for adaptive manufacturing system control. *International journal of production research 49*, 5 (2011), 1255–1268.

[183] Tawegoum, R., Castelain, E., and Gentina, J. Hierarchical and dynamic production control in flexible manufacturing systems. *Robotics and computer-integrated manufacturing 11*, 4 (1994), 327–334.

[184] Terziyan, V., Gryshko, S., and Golovianko, M. Patented intelligence: Cloning human decision models for Industry 4.0. *Journal of Manufacturing Systems 48* (July 2018), 204–217.

[185] Testa, Q., and Aoudia, H. *Perfect QRQC-vol 1-Les fondations: Quick Response Quality Control-La management qualité basé sur l'attitude San Gen Shugi.* Maxima, 2012.

[186] Toh, K. T. K., Newman, S. T., and Bell, R. An information systems architecture for small metal-working companies. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 212*, 2 (Feb. 1998), 87–103.

[187] Trentesaux, D. *Pilotage hétérarchique des systèmes de production.* PhD thesis, Université de Valenciennes et du Hainaut-Cambresis, 2002.

[188] Trentesaux, D. Les systèmes de pilotage hétérarchiques: innovations réelles ou modèles stériles? *Journal Européen des Systèmes Automatisés (JESA) 41*, 9-10 (2007), 1165–1202.

[189] Trentesaux, D. Distributed control of production systems. *Engineering Applications of Artificial Intelligence 22*, 7 (2009), 971–978.

[190] Trentesaux, D., and Karnouskos, S. Engineering ethical behaviors in autonomous industrial cyber-physical human systems. *Cognition, Technology & Work* (Mar. 2021).

[191] Trentesaux, D., and Millot, P. A Human-Centred Design to Break the Myth of the "Magic Human" in Intelligent Manufacturing Systems. In *Service Orientation in Holonic and Multi-Agent Manufacturing*, T. Borangiu, D. Trentesaux, A. Thomas, and D. McFarlane, Eds., vol. 640. Springer International Publishing, Cham, 2016, pp. 103–113.

[192] Trentesaux, D., Tahon, C., and Ladet, P. Hybrid production control approach for jit scheduling. *Artificial Intelligence in Engineering 12*, 1-2 (1998), 49–67.

[193] Tursi, A. *Ontology-Based approach for Product-Driven interoperability of enterprise production systems.* PhD thesis, Université Henri Poincaré-Nancy 1; Politecnico di Bari, 2009.

[194] Valckenaers, P. Arti reference architecture–prosa revisited. In *International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing* (2018), Springer, pp. 1–19.

[195] Valckenaers, P. Perspective on holonic manufacturing systems: Prosa becomes arti. *Computers in Industry 120* (2020), 103226.

[196] Valckenaers, P., and Brussel, H. V. *Design for the Unexpected: From Holonic Manufacturing Systems towards a Humane Mechatronics Society.* Butterworth-Heinemann, Nov. 2015. Google-Books-ID: kBBpBwAAQBAJ.

[197] Valckenaers, P., and Van Brussel, H. Holonic Manufacturing Execution Systems. *CIRP Annals 54*, 1 (2005), 427–432.

[198] Valckenaers, P., Van Brussel, H., Verstraete, P., Saint Germain, B., et al. Schedule execution in autonomic manufacturing execution systems. *Journal of manufacturing systems 26*, 2 (2007), 75–84.

[199] Valette, E., Bril El-Haouzi, H., and Demesure, G. L'humain dans les systèmes de production basés sur les paradigmes IoT et CPS: état des lieux et perspectives. In *13ème Conférence Francophone de Modélisation, Optimisation et Simulation - MOSIM'20* (2020), p. 8.

[200] Valette, E., Bril El-Haouzi, H., and Demesure, G. Toward a Social Holonic Manufacturing Systems Architecture Based on Industry 4.0 Assets. In *Service Oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future* (Cham, 2021), T. Borangiu, D. Trentesaux, P. Leitão, O. Cardin, and S. Lamouri, Eds., Studies in Computational Intelligence, Springer International Publishing, pp. 286–295.

[201] Valette, E., Demesure, G., El-Haouzi, H. B., and Pannequin, R. Formal and modelling frameworks for Social Holonic Control Architectures. *Computers in Industry 132* (Nov. 2021), 103521.

[202] Van Brussel, H., Wyns, J., Valckenaers, P., Bongaerts, L., and Peeters, P. Reference architecture for holonic manufacturing systems: PROSA. *Computers in Industry 37*, 3 (Nov. 1998), 255–274.

[203] Vanderhaegen, F. Pedagogical learning supports based on human–systems inclusion applied to rail flow control. *Cognition, Technology & Work* (Sept. 2019), 1–10.

[204] Verstraete, P., Germain, B. S., Valckenaers, P., Brussel, H. V., Belle, J. V., and Hadeli, N. Engineering manufacturing control systems using PROSA and delegate MAS. *International Journal of Agent-Oriented Software Engineering 2*, 1 (2008), 62.

[205] Wang, B., Sun, Y., Li, S., and Cao, Q. Hierarchical Matching With Peer Effect for Low-Latency and High-Reliable Caching in Social IoT. *IEEE Internet of Things Journal 6*, 1 (Feb. 2019), 1193–1209. Conference Name: IEEE Internet of Things Journal.

[206] Wang, B., Sun, Y., Sun, Z., Nguyen, L. D., and Duong, T. Q. UAV-Assisted Emergency Communications in Social IoT: A Dynamic Hypergraph Coloring Approach. *IEEE Internet of Things Journal 7*, 8 (Aug. 2020), 7663–7677. Conference Name: IEEE Internet of Things Journal.

[207] Wang, F.-Y. The Emergence of Intelligent Enterprises: From CPS to CPSS. *IEEE Intelligent Systems 25*, 4 (July 2010), 85–88.

[208] Wang, Q., Jiao, W., Yu, R., Johnson, M. T., and Zhang, Y. Modeling of Human Welders' Operations in Virtual Reality Human–Robot Interaction. *IEEE Robotics and Automation Letters 4*, 3 (July 2019), 2958–2964. Conference Name: IEEE Robotics and Automation Letters.

[209] Wang, Q., Jiao, W., Yu, R., Johnson, M. T., and Zhang, Y. Virtual Reality Robot-Assisted Welding Based on Human Intention Recognition. *IEEE Transactions on Automation Science and Engineering 17*, 2 (Apr. 2020), 799–808. Conference Name: IEEE Transactions on Automation Science and Engineering.

[210] Wang, T., Li, J., Deng, Y., Wang, C., Snoussi, H., and Tao, F. Digital twin for human-machine interaction with convolutional neural network. *International Journal of Computer Integrated Manufacturing 34*, 7-8 (Aug. 2021), 888–897. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/0951192X.2021.1925966.

[211] Wei, L., Wu, J., Long, C., and Li, B. On Designing Context-Aware Trust Model and Service Delegation for Social Internet of Things. *IEEE Internet of Things Journal 8*, 6 (Mar. 2021), 4775–4787. Conference Name: IEEE Internet of Things Journal.

[212] White Paper Work 4.0. White Paper Work 4.0. White Paper, Federal Ministry of Labour and Social Affairs, Berlin, Mar. 2017.

[213] Wooldridge, M. J., and Jennings, N. R. Intelligent Agents: Theory and Practice. *The Knowledge Engineering Review 10*, 2 (1995), 115–152. Number: 2.

[214] Xu, Z., Liu, A., Yue, X., Zhang, Y., Wang, R., Huang, J., and Fang, S.-H. Combining Proximity Estimation With Visible Symbol Assignment to Simplify Line-of-Sight Connections in Mobile Industrial Human-Machine Interaction. *IEEE Access 7* (2019), 133559–133571. Conference Name: IEEE Access.

[215] Yang, H., Zhong, W.-D., Chen, C., Alphones, A., and Xie, X. Deep-Reinforcement-Learning-Based Energy-Efficient Resource Management for Social and Cognitive Internet of Things. *IEEE Internet of Things Journal 7*, 6 (June 2020), 5677–5689. Conference Name: IEEE Internet of Things Journal.

[216] Yang, P., Liu, J., Qi, J., Yang, Y., Wang, M., and Lv, Z. Comparison and Modelling of Country-Level Micro-blog User Behaviour and Activity in Cyber-Physical-Social Systems using Weibo and Twitter Data. *ACM Transactions on Intelligent Systems and Technology 10* (June 2019).

[217] Yang, T., Ma, J., Hou, Z.-G., Peng, G., and Tan, M. A multi-agent architecture based cooperation and intelligent decision making method for multirobot systems. In *International Conference on Neural Information Processing* (2007), Springer, pp. 376–385.

[218] Yang, W., Huang, H., Jing, X., Li, Z., and Zhu, C. Social Interaction Assisted Resource Sharing Scheme for Device-to-Device Communication Towards Green Internet of Things. *IEEE Access 8* (2020), 71652–71661. Conference Name: IEEE Access.

[219] Yao, B., Zhou, Z., Wang, L., Xu, W., Yan, J., and Liu, Q. A function block based cyber-physical production system for physical human–robot interaction. *Journal of Manufacturing Systems 48* (July 2018), 12–23.

[220] Yi, Y., Zhang, Z., and Gan, C. The outbreak threshold of information diffusion over social–physical networks. *Physica A: Statistical Mechanics and its Applications 526* (July 2019), 121128.

[221] Yin, D., Ming, X., and Zhang, X. Understanding Data-Driven Cyber-Physical-Social System (D-CPSS) Using a 7C Framework in Social Manufacturing Context. *Sensors 20*, 18 (Jan. 2020), 5319. Number: 18 Publisher: Multidisciplinary Digital Publishing Institute.

[222] Yoshikawa, H. Manufacturing and the 21st century — Intelligent manufacturing systems and the renaissance of the manufacturing industry. *Technological Forecasting and Social Change 49*, 2 (June 1995), 195–213.

[223] Żabiński, T., and Mączka, T. Implementation of human-system interface for manufacturing organizations. In *Human–Computer Systems Interaction: Backgrounds and Applications 2*. Springer, 2012, pp. 13–31.

[224] Zambrano, G., Pach, C., Aissani, N., Berger, T., and Trentesaux, D. An approach for temporal myopia reduction in heterarchical control architectures. In *2011 IEEE international symposium on industrial electronics* (2011), IEEE, pp. 1767–1772.

[225] Zheng, X., Wang, M., and Ordieres-Meré, J. Comparison of Data Preprocessing Approaches for Applying Deep Learning to Human Activity Recognition in the Context of Industry 4.0. *Sensors 18*, 7 (July 2018), 2146. Number: 7 Publisher: Multidisciplinary Digital Publishing Institute.

[226] Zhukova, N., Thaw, A. M., Tianxing, M., and Nikolay, M. IoT Data Collection Based on Social Network Models. In *2020 26th Conference of Open Innovations Association (FRUCT)* (Apr. 2020), pp. 458–463. ISSN: 2305-7254.

[227] Zimmermann, E. *Modèles d'optimisation et d'évaluation de système de pilotage intelligent en contexte de flux fortement perturbés par les reprises.* PhD thesis, Université de Lorraine, 2019.

Appendix A

Agent classes and State machines

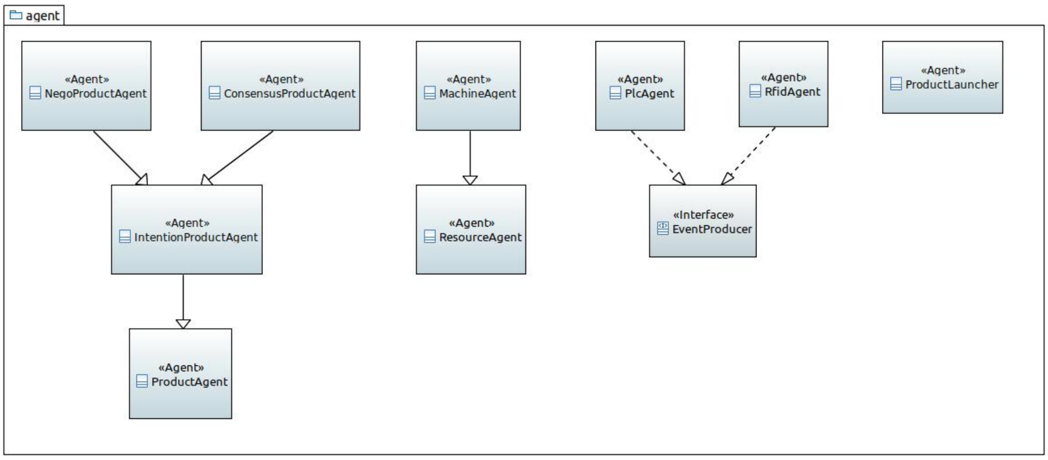


Figure A.1: Agent classes overview

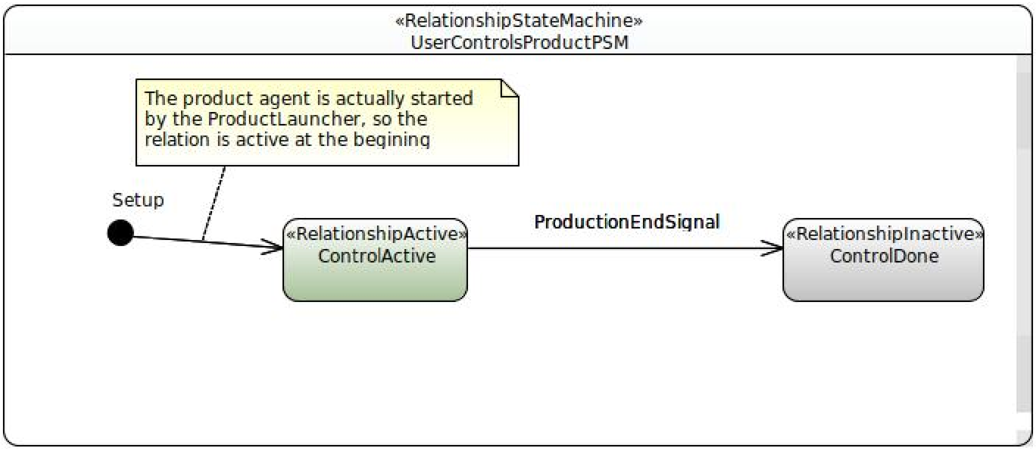


Figure A.2: State Machine for HR relationships establishment between *Product Launcher* and *Product* holons

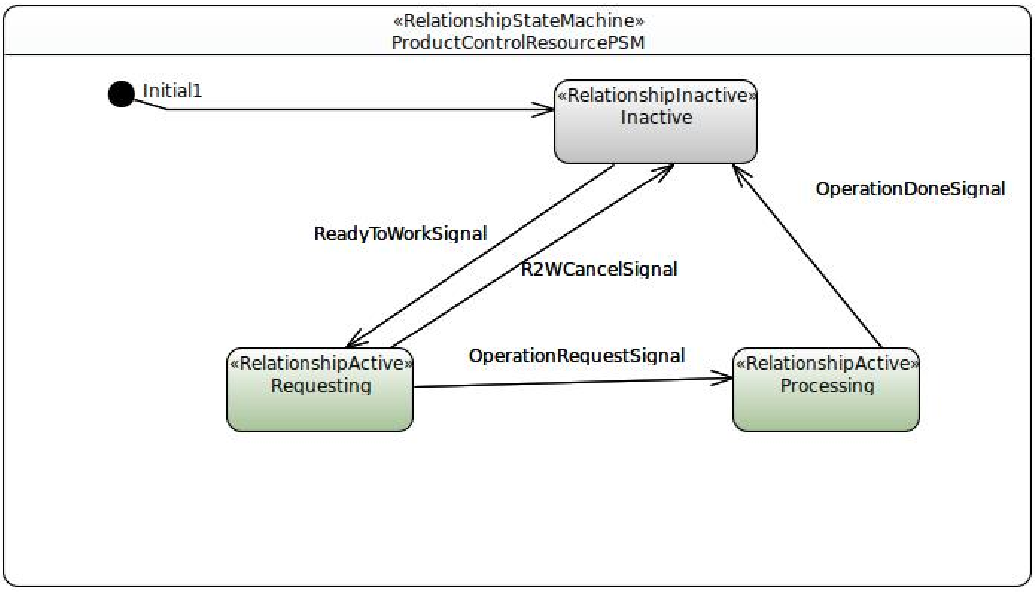


Figure A.3: State Machine for HR relationships establishment between *Product* and *Resource* holons

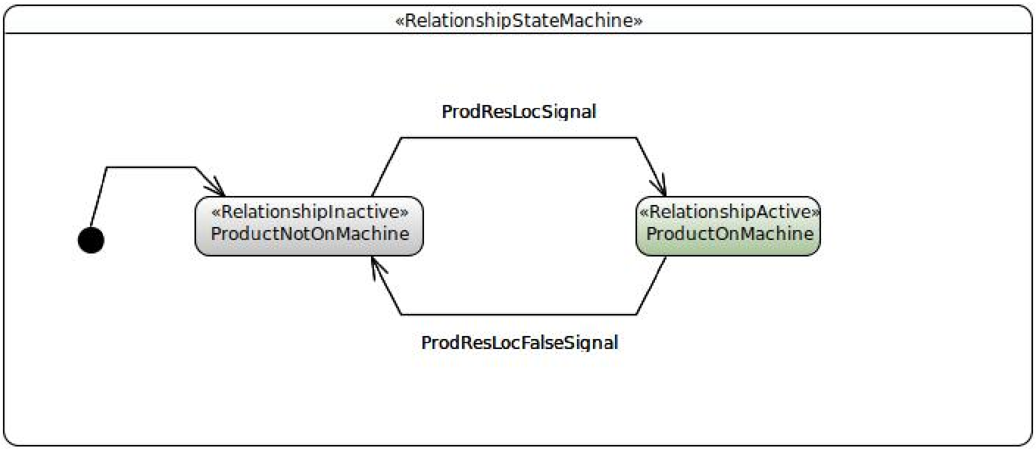


Figure A.4: State Machine for OR relationships establishment between *Product* and *Resource* holons

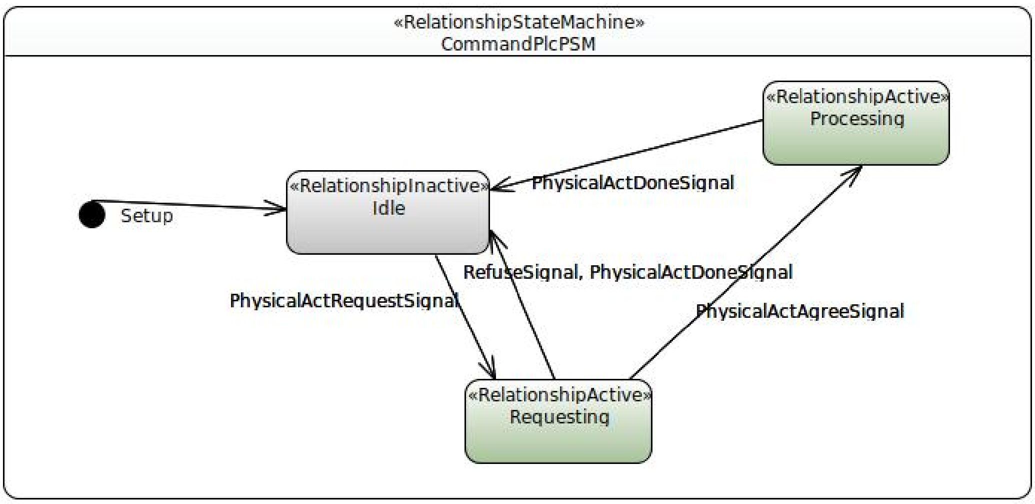


Figure A.5: State Machine for HR relationships establishment between *PLC* and *Resource* holons

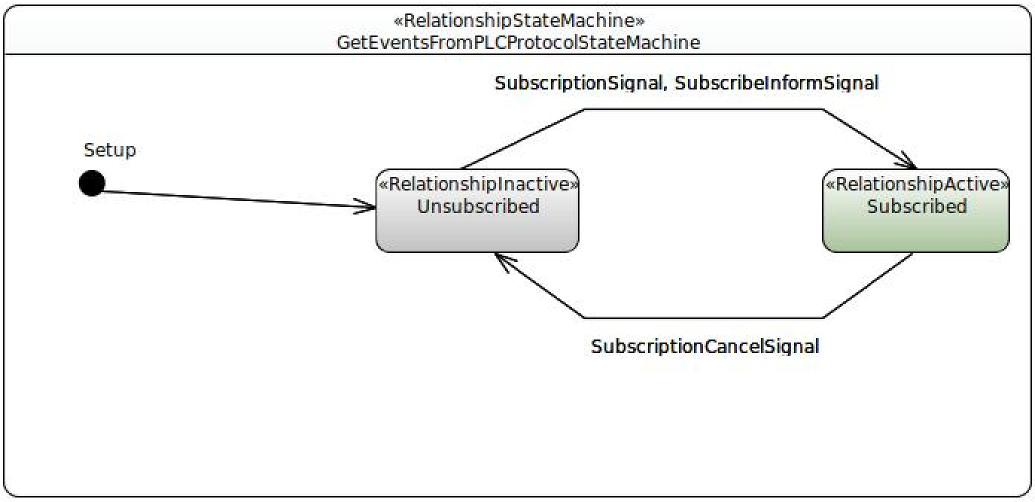


Figure A.6: State Machine for DR relationships establishment between *PLC* and *Resource* holons

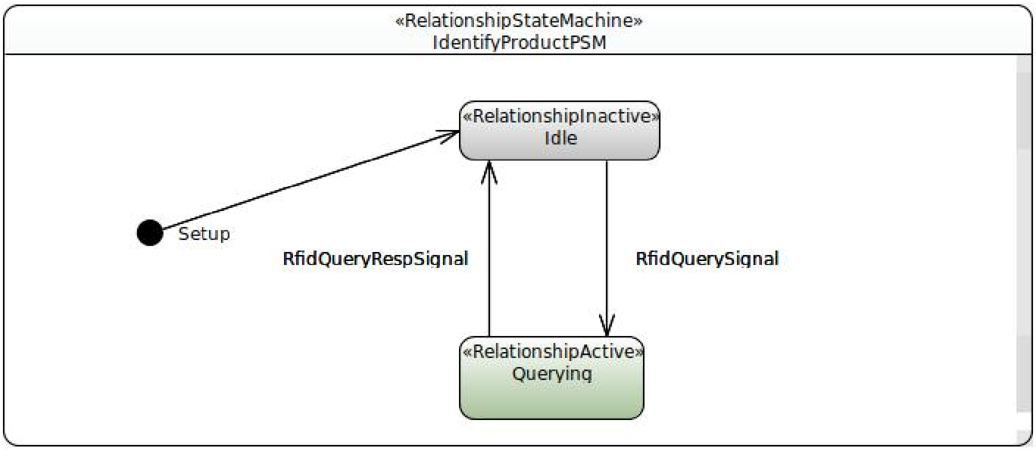


Figure A.7: State Machine for DR relationships establishment between *RFID* and *Resource* holons

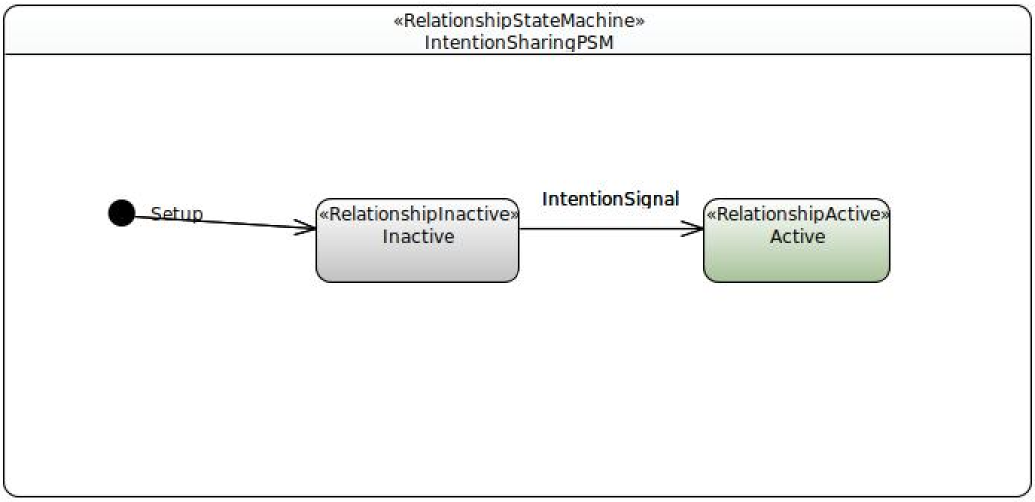


Figure A.8: State Machine for DR relationships establishment between *Intention Product* and *Machine* holons, or among *Consensus Product* ones

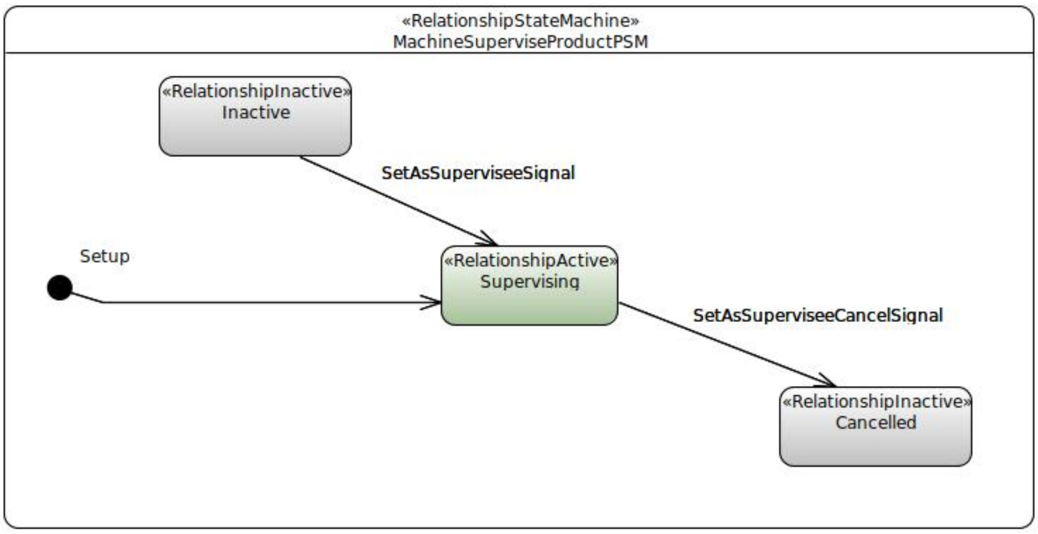


Figure A.9: State Machine for HR relationships establishment between *Nego Product* and *Machine* holons

Appendix B

Types of events occurring through the platform

Table B.1: Types of events occurring through the platform

	signal : Signal [1]	direction : MessageDirection [1]
ReadyToWorkSignalEvent	ReadyToWorkSignal	ag2_to_ag1
OperationAgreeSignalEvent	OperationAgreeSignal	ag1_to_ag2
OperationDoneSignalEvent	OperationDoneSignal	ag2_to_ag1
OperationRequestSignalEvent	OperationRequestSignal	ag1_to_ag2
R2WCancelSignalEvent	R2WCancelSignal	ag1_to_ag2
SubscriptionSignalEvent	SubscriptionSignal	ag1_to_ag2
SubscriptionCancelSignalEvent	SubscriptionCancelSignal	ag1_to_ag2
PhysicalActRequestSignalEvent	PhysicalActRequestSignal	ag1_to_ag2
PhysicalActAgreeSignalEvent	PhysicalActAgreeSignal	ag2_to_ag1
PhysicalActDoneSignalEvent	PhysicalActDoneSignal	ag2_to_ag1
RfidSubscribeSignalEvent	RfidSubscribe	ag1_to_ag2
ProdResLocSignalEvent	ProdResLocSignal	ag1_to_ag2
ProdResLocFalseSignalEvent	ProdResLocFalseSignal	ag1_to_ag2
RefuseSignalEVent	RefuseSignal	ag2_to_ag1
SubscribeInformSignalEvent	SubscribeInformSignal	ag2_to_ag1
RfidQuerySignalEvent	RfidQuerySignal	ag1_to_ag2
RfidQueryRespSignalEvent	RfidQueryRespSignal	ag2_to_ag1
ProductionEndSignalEvent	ProductionEndSignal	ag2_to_ag1
IntentionSignalEvent	IntentionSignal	ag2_to_ag1
SetAsSuperviseeCancelSignalEvent	SetAsSuperviseeCancelSignal	ag2_to_ag1
SetAsSuperviseeSignalEVent	SetAsSuperviseeSignal	ag2_to_ag1

Appendix C

Types of signals exchanged across the platform

Table C.1: Types of signals exchanged across the platform - 1

	Performative	Protocol	Language	Ontology	ActionType	ContentType	DoneType
ReadyToWorkSignal	INFORM		fipa-sl	ProductConfOntology		ReadyToWork	
OperationAgreeSignal	AGREE	fipa-request					
OperationDoneSignal	INFORM		fipa-sl	ProductConfOntology			
OperationRequestSignal	REQUEST		fipa-sl	ProductConfOntology			
R2WCancelSignal	CANCEL		fipa-sl	ProductConfOntology		ReadyToWork	
SubscriptionSignal	SUBSCRIBE	fipa-subscribe					
SubscriptionCancelSignal	CANCEL	fipa-subscribe					
PhysicalActRequestSignal	REQUEST	fipa-request	fipa-sl	PlcOntology	PhysicalAction		
PhysicalActAgreeSignal	AGREE						
PhysicalActDoneSignal	INFORM	fipa-request	fipa-sl	PlcOntology			PhysicalAction
RfidSubscribe	SUBSCRIBE	fipa-subscribe					
ProdResLocSignal	INFORM		fipa-sl	ProductConfOntology		ResPositionEvent	
ProdResLocFalseSignal	INFORM		fipa-sl	ProductConfOntology		ResPositionEvent	
RefuseSignal							
SubscribeInformSignal	INFORM	fipa-subscribe					
RfidQuerySignal	QUERY-REF		fipa-sl	RfidOntology			
RfidQueryRespSignal	INFORM		fipa-sl	RfidOntology			
ProductionEndSignal	INFORM		fipa-sl	ProductConfOntology			
IntentionSignal	INFORM		fipa-sl	ProductConfOntology			
SetAsSuperviseeCancelSignal	CANCEL		fipa-sl	ProductConfOntology	SetAsSupervisee		
SetAsSuperviseeSignal	REQUEST	fipa-request	fipa-sl	ProductConfOntology	SetAsSupervisee		

Table C.2: Types of signals exchanged across the platform - 2

<table>
<tr><th></th><th>Content</th></tr>
<tr><td>ReadyToWorkSignal</td><td></td></tr>
<tr><td>OperationAgreeSignal</td><td></td></tr>
<tr><td>OperationDoneSignal</td><td><code>\(\((done|result) \(action \(.*\) \((Assembly|Routing|Agg)Operation.*</code></td></tr>
<tr><td>OperationRequestSignal</td><td><code>\(\(action \(.*\) \((Assembly|Routing|Agg)Operation.*\end{verbatim}</code></td></tr>
<tr><td>R2WCancelSignal</td><td></td></tr>
<tr><td>SubscriptionSignal</td><td></td></tr>
<tr><td>SubscriptionCancelSignal</td><td></td></tr>
<tr><td>PhysicalActRequestSignal</td><td></td></tr>
<tr><td>PhysicalActAgreeSignal</td><td></td></tr>
<tr><td>PhysicalActDoneSignal</td><td></td></tr>
<tr><td>RfidSubscribe</td><td></td></tr>
<tr><td>ProdResLocSignal</td><td><code>ResPositionEvent .* true .*</code></td></tr>
<tr><td>ProdResLocFalseSignal</td><td><code>ResPositionEvent .* false .*</code></td></tr>
<tr><td>RefuseSignal</td><td></td></tr>
<tr><td>SubscribeInformSignal</td><td></td></tr>
<tr><td>RfidQuerySignal</td><td><code>\(\(all \?x \(RfidEvent \?x \(Resource :area .* :name .*\) true\)\)\)</code></td></tr>
<tr><td>RfidQueryRespSignal</td><td><code>\(\(= \(all \?x \(RfidEvent \?x \(Resource :area .* :name .*\) true\)\) \(set .*\)\)\)</code></td></tr>
<tr><td>ProductionEndSignal</td><td><code>\(\(= \(iota \(sequence \?x \?y\) \(ProductionEnd \?y \?x\)\) \(sequence .* .*\)\)\)</code></td></tr>
<tr><td>IntentionSignal</td><td><code>\(\(= \(iota \(sequence .*\) \(Intention .*\)\) \(sequence .*\)\)\)</code></td></tr>
<tr><td>SetAsSuperviseeCancelSignal</td><td></td></tr>
<tr><td>SetAsSuperviseeSignal</td><td></td></tr>
</table>

Abstract

Toward an anthropocentric approach for intelligent manufacturing systems' control architectures

Last decades have seen the growth in size and complexity of industrial systems and flows (both physical and informational). Hyper competitive markets, demand atomization and customer requirements level increase have brought about the need to combine the robustness and performance of centralized systems with the responsiveness of decentralized systems. For the 20 last years, the relevance of these Hybrid Control Architectures (HCA) has been demonstrated through numerous works. However, they are today hardly present in the industrial landscape. This situation could find some of its roots in a certain lack of genericity and/or Human-System acceptability.

In this research work, the explored path consists in proposing a reference formal framework for the design, modelling, simulation, visualization and evaluation of complex systems' constitutive components and interactions/relations. The purpose of this framework is to bridge the genericity gap identified for Holonic and Hybrid Control Architectures Design regarding complex Multi-Agent Systems (MAS), but also to promote human inclusion into these. To this end and to promote the socio-technical representation of systems, the proposed relationships model is grounded on the nature human societies' ones.

Keywords *Holonic Control Architectures*, *Hybrid Control Architectures*, *Human-Centred approaches*, *Socio-Technical Systems*, *Industry 4.0*, *Industry 5.0*.

Résumé

Vers une approche anthropocentrée des architectures de contrôle pour les systèmes intelligents de production

Les dernières décennies ont vu croître en taille et en complexité les systèmes industriels ainsi que leurs flux (matériels et informationnels). L'hyper compétitivité des marchés, l'atomisation de la demande et l'augmentation des niveaux d'exigences clients ont fait émerger le besoin de coupler la robustesse et la performance des systèmes centralisés à la réactivité des systèmes décentralisés. Au cours des 20 dernières années, la pertinence de ces Architectures de Contrôle Hybrides (HCA) a pu être démontrée à travers de nombreux travaux. Toutefois, leur déploiement reste aujourd'hui limité. Cette situation semble pouvoir être rapporté à un manque de généricité ou d'acceptabilité Humain/Système.

La piste explorée dans ce travail de recherche consiste à proposer un cadre formel de référence pour la conception, modélisation, simulation, visualisation et évaluation des composants et des interactions/relations constitutifs des systèmes complexes. L'objectif de ce cadre est d'apporter la généricité manquant aujourd'hui pour le design des architectures de contrôle holoniques et hybrides pour les systèmes multi-agents complexes, mais également de favoriser l'inclusion de l'humain dans ces derniers. Pour ce faire, la nature des relations proposées s'appuie sur celles observables au sein des sociétés humaines, afin de favoriser la représentation des systèmes comme socio-techniques.

Mots-clés*Architectures de contrôle holoniques*, *Architectures de contrôle hybrides*, *Approches centrées-humain*, *Systèmes Socio-techniques*, *Industrie 4.0*, *Industrie 5.0*.

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