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Neuro-inspired Framework for Cognitive Manufacturing Control

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Abstract

There are currently certain categories of manufacturing enterprises whose structure, organization and operating context have an extremely high degree of complexity, especially due to the way in which their various components interact and influence each other. For them, a series of paradigms have been developed, including intelligent manufacturing, smart manufacturing, cognitive manufacturing; which are based equally on information and knowledge management, management and interpretation of data flows and problem solving approaches. This work presents a new vision regarding the evolution of the future enterprise based on concepts and attributes acquired from the field of biology. Our approach addresses in a systemic manner the structural, functional, and behavioral aspects of the enterprise, seen as a complex dynamic system. In this article we are proposing an architecture and management methodology based on the human brain, where the problem solving is achieved by Perception – Memory – Learning and Behavior Generation mechanisms. In order to support the design of such an architecture and to allow a faster learning process, a software modeling and simulation platform was developed and is briefly presented.

Keywords: Perception, Internet of Things, Control Architecture, Bio-inspired manufacturing control.

1 Introduction

Modern control strategies and advanced technological progress of the last 50 years had a crucial impact on the socio-economic development. Systems engineering and advanced control are playing an important role in all aspects of our life and evolution, thus generating increasingly high expectations with respect to the categories of problems they can solve.

As a driver and support of development, manufacturing systems have particularly evolved and diversified, the range of enterprises existing today being, in a sense, equally varied in terms of size, organization, complexity, distribution (networking), dependence on resources and location, as biological eco-systems.

Even from the point of view of (social) organization, small artisanal workshops or micro-enterprises that often use high-tech cutting edge components for niche products coexist with large corporations producing complex equipment or form dynamically reconfigurable cooperative structures such as virtual enterprises.

For this reason, there is a continuous evolution of the modeling and management paradigms of enterprises, in parallel with the development of a huge number of software support applications, both for specific activities / work structures at the manufacturing level, and for their integration into unified architectures, with coherent and correlated evolution [7, 11].

This paper considers the category of manufacturing enterprises that can be qualified as complex systems, for reasons related to the production structure (small and medium batches of highly customizable products), technological and design flexibility, production capacity, variety of logistics and supply chains available. This category of organizations, in which the execution of a product can be performed in various ways, depending on contexts defined by the state of resources, the cost of operations and transport, the dead-line of orders, the availability of raw materials, etc. is the one for which the paradigm of flexible manufacturing has been continuously developed, towards intelligent manufacturing, smart manufacturing, and cognitive manufacturing, following a trend that leads, ultimately, to the development of autonomous enterprises.

The intention of this paper is to continue the trend and, treating the manufacturing system as a biological / social organism, to propose a control approach inspired by the human brain, taking into account especially processes known as perception (sensory interpretation), reasoning (problem solving related models) and learning (problem modeling, generalization, meta-models).

The proposed approach intends to take into account how the huge amounts of data that enterprise IT systems convey can be used effectively to solve problems, both in terms of relevance and resolution time-horizons, which is why perception becomes a key-concept to generate optimal behaviors.

In addition, we consider important to ensure that the mode of operation and communication of the manufacturing enterprise control system is as close as possible to the way human specialists reason, thus facilitating human-machine communication.

Section 2 is dedicated to the presentation of the most important paradigms derived from the Flexible Manufacturing Systems, which are suitable in manufacturing facilities with complex structure and intelligent behavior. The specificities and characteristics of these paradigms are highlighted, which are further developed within our integrative concept of neuro-inspired cognitive control.

Section 3 describes an enterprise model which is based on the functional perspective of the human nervous system, where shop-floor manufacturing generates problems such as reflex / unconscious actions, operational level - problems such as those to be solved by instantiating validated procedures (learned behavior), and the strategic level - new problems.

Starting from the way the neuroscience describes the functioning mechanisms of the human brain and the connection between conscious and subconscious, our approach explains the cycle of Perception - Memory - Learning and Behavior Generation on which the presented framework is based. The conceptualization of perception is considered as a key element in problem solving and how problems can move to various levels of conceptualization, from new problems to reflex actions.

Section 4 briefly presents a software platform conceived to support and test the hybrid modeling approach that allows developing a cognitive control framework. Some general conclusions on the concept and a recap of the contributions of this article are presented in Section 5.

2 Cognitive manufacturing: a brief review

Cognitive Manufacturing is a relatively recent term, usually referred in the context of Industry 4.0. It is used to denominate a combination of techniques, including Internet of Things (IoT), Deep Learning, data/ process mining, analytics a.s.o, which is intended to efficiently use the actually available large quantities of enterprise information in decisional processes. A special attention is awarded to information networking and identifying correlations between processes and actions that are ongoing in different departments.

There are already several large companies such as IBM (which has practically introduced the term), Emerson or Deloitte which are using the term for a set of software applications they are developing. [6, 12, 24, 30].

Such commercial solutions are naturally oriented towards proprietary ontologies and are taking into account mostly the customized integration of the enterprise IT system and procedures [5, 31]. From this point of view, they are extending other available computer-supported solutions as business intelligence, enterprise resource planning, smart manufacturing, a.s.o. In the cognitive field there are various approaches, some of them rather punctual [14, 29]. In this paper the main goal is to conceive a framework allowing the management of large-scale integrative systems that adopt such results.

At the beginning of 1970 years, the main problems of manufacturing (enterprise) control were the lack of sufficient data and the cost / availability of computer technology to run control algorithms. In time, technological evolution that resulted in sensor networks powered by IoT and the decreasing costs and increasing power of computer technology has somehow reversed this problem. Enterprises are collecting and storing huge amounts of data, from which only a low percentage is analyzed. Big Data, process mining and analytics are trying to solve this problem, which is increasingly frustrating from enterprise control point of view, because this information may help problem solving, but it may also be irrelevant and only futilely add cost and delay in finding solutions.

Cognitive manufacturing represents, from this point of view, a step towards a revolution of knowledge in a framework defined by paradigms as Industrie 4.0 and Cyber-Physical Systems [16]. They are expanding the concept of Intelligent Manufacturing, which, according to [26], should have the capability to integrate decision making systems in order to obtain knowledge. Also, Intelligent Manufacturing Systems require to learn and to adapt based on the changing environment, as well as based on the required outputs and configurability of each component; should be able to self-develop and to generate information in an intelligent manner in order to control all production systems.

Thus, Industrial Internet, the Internet of Services and the extension towards the Internet of Knowledge could create a real field of opportunity for the next generation of enterprises.

Researchers in Intelligent manufacturing control have considered biology as inspiration for paradigms emerging in recent years; paradigms as Genetic Manufacturing Systems (GMS), Biological Manufacturing (BM), reconfigurable manufacturing systems (RMS), holonic manufacturing system (HMS), evolvable manufacturing system (EMS), cloud manufacturing system (CMS), cognitive manufacturing systems (CMS) and autonomous manufacturing system (AMS). All the paradigms can be seen as intelligent manufacturing systems (IMS) that can be modeled based on living systems. For example, GMS and BMS are modeled after natural principles, thus manufacturing systems are seen as biological organisms. Thus, IMS represent a link in the transformation from automation to autonomy of these systems.

In [19], authors discuss intelligent scheduling in relation to process optimization, control techniques, and maintenance models. Also, in order to define the concept of intelligent scheduling they have analyzed the multi-objective ant colony optimization (ACO) algorithm and an ACO-based optimization algorithm hybrid with local searching technique. Also, they analyzed a discrete artificial bee colony algorithm (DABC) to minimize the weight earliness and tardiness penalties in flow shop scheduling problem, as well as a novel simulated annealing (NSA) algorithm with new operators in order to propose solutions to reduce the makespan of a hybrid flow shop. Based on these models, authors have proposed an Intelligent Prediction and Optimization algorithm based on Neural Networks (NN) and thus, they propose a NN based adaptive controller for online prediction and control.

Recent developments in Cyber-Physical Systems (CPS) are focused on the study of the interaction of physical and virtual components and modeling as complex systems and the integration in systems of systems, thus addressing a wide range of temporal and spatial scales [21]. The structure of a Cyber-Physical System is complex; as complex as the structure of a living mammalian organism, and, as such, has the same need for a specially organized and continuously developing control system.

According to [15], cognitive science represents a highly interdisciplinary field, combining ideas and methods from various domains, such as psychology, engineering and computer science, linguistics, philosophy, and neuroscience. From this point of view, Cognitive Control allows the mind to override impulses and take decisions based on the objectives, rather than reactions. Cognitive Control offers the possibility to select a certain behavior that has been accepted as appropriate and reject a behavior that has been considered as inappropriate. Thus, Cognitive Control becomes the center of self-awareness, represented as the top layer including consciousness and willpower.

The vision presented in this paper is deriving from these concepts, creating a parallel between the manufacturing Enterprise Control System and Central Neural System of a living organism, whose actions are generated through reflexes, learned behaviour and new strategies as presented in Figure 1.

The approach addressed in this paper is considering the global socio-economical context as described by the Industrie 4.0 paradigm, the Cyber-physical approach in enterprise modelling – for a class of enterprises whose goals and behaviors have an important degree of complexity (Intelligent Cyber-Enterprises) and which are using new technologies as Internet of Things, Internet of Services, Industrial Internet of Things or Cloud Computing in order to connect their modules and reconfigure their structure – and the appropriate knowledge management for controlling large interconnected structures acting in highly dynamical environments. These new technologies and paradigms and the pronounced evolution of the ICT (Information and communications technology) are enabling and supporting this new approach.

We are considering that the evolution of manufacturing enterprises from the factories of the XIX-th century to the Intelligent Cyber-Enterprises that are emerging now is following the development of biological organisms. Consequently, as the complexity of the controlled systems and of their goals increase, the bio-inspired approaches in their control have to evolve towards the capabilities of human brain, which are the model for the control approach which we are presenting.

A special focus is on the capability to interpret basic data, as they are today available in large amounts at enterprise level, as information and relevant knowledge and to use them appropriately in problem solving. As such, the above mentioned Big Data techniques, structured by means of corporate knowledge management are used to support control systems in problem solving – where problems are defined in terms of workflows, orders and supply chain management specifications.

3 Perception-oriented architectural approach for cognitive enterprise

3.1 The cognitive enterprise – functional and modeling requirements

It is important to clearly specify that the manufacturing enterprise which needs this cognitive approach is an enterprise whose object of activity is a complex product, embedding physical and IT parts (automotive industry is one of the possible case studies), with a high level of customization. Such enterprises are usually globally distributed from the point of view of production capabilities and are organized as extended networks, with large and flexible supply chains. They have high level

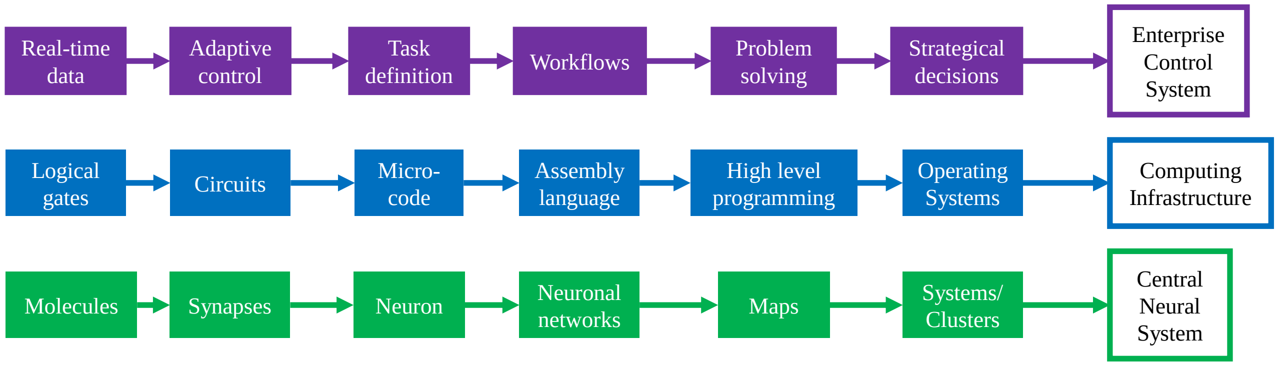

Figure 1: A parallel between the enterprise control system and the central neural system.

automation at the shop-floor level and a high(er) level of informatization, which is issuing a tremendous amount of data [20].

Their problems are ranging from actual workflow management decisions under tight cost / quality optimization constraints to strategic decisions with regards to new production capabilities, extension of supplier's network, subcontracting, adoption of new technologies, relocation etc., each of them having impact on the workflow management and depending on a very dynamic environment.

As supplementary specifications, usually they have:

- high technological and design flexibility, which gives great complexity to product workflows (i.e. there may exist multiple ways to implement the same product) and cases - every choice resulting in actual constraints for the supply chain management;
- the supply chain management represents a very important factor for the overall enterprise performance and depends on the global context [17];
- the functioning scenario for which control decisions should be made, and which include the current state of enterprise resources / order situation (products, quantities, delivery place and time, a.s.o) / production context is always different; these differences may be quantitative only, but they may also become qualitative, depending on context.

In certain contexts, changes that could have been interpreted as parametric (quantitative), become qualitative, thus imposing structural changes in the models used and, as such, changing the approaches used in solving problems. Correct perception of context is thus becoming crucial in finding a concrete solution for a given business situation.

In short, cognitive manufacturing is a solution for these manufacturing enterprises for which:

- the problems to be solved are not repetitive, but have repetitive components
- the dynamics of the manufacturing system environment is rapid
- the manufacturing system is reconfigurable, has technological flexibility and / or product flexibility
- human in the loop is crucial for decision
- (very) large amounts of (heterogeneous) information are available
- multiple functioning optimization criteria are requested
- multiple problem-solving approaches are available
- local automation and integrative communication are available

From a systemic point of view, the cognitive enterprise has the characteristics of a complex system. It has developed on several levels of resolution, and may be considered both a collection of systems and a meta-system, depending on the degree of interconnection of the components.

The major challenges in their analysis and management appear due to their large size, diverse dynamics, distributed on different levels of resolution, geographical distribution and diversity of processes and products, the presence of uncertainties, strict safety requirements and required functional reliability. Complexity manifests itself differently, depending on the level of resolution considered: at the component level it is the result of a process of designing a solution based on well-defined objectives, and at the global level, the complexity is the result of emergence. At the component level, solving a problem can be algorithmized - implemented as a process model – the problems being structurally repetitive. At the group level of components (collection or meta-system), defining a problem itself becomes difficult, and requires special approaches (learning, trial and error).

From an engineering point of view, the most appropriate paradigm for representing a complex cognitive enterprise system is that of Intelligent Cyber-Physical Systems, which takes over already existing technological elements and gives them new values, through adaptation, development and incorporation.

Returning to the biological perspective, a similar intelligent system, the human body, can be modeled at different scales: cell, organ, system and the whole organism; each characterized, on the one hand, by clear local objectives which are related to their specific functionality, but, on the other hand, each characterized by the contribution to the emergent functioning of the whole organism, whose objectives vary permanently, in relation to the environment in which it is placed. Even if the geographical distribution of the components does not cover a very large area, the specific issues, the diversity of objectives, the presence of uncertainties and even the needs of safety and reliability remain.

The control system of the human body, the brain, has developed so that it can manage this complex system, in a way that allows both the optimization of functioning in known contexts and the permanent identification of new solutions. In addition, it has perfected a series of mechanisms that allow it to efficiently manage the huge volume of information it has at its disposal.

Different components coordinated by the Central Nervous System have a real local autonomy; they are achieving, by interaction different complex goals, through the reconfiguring capacity of the brain. Configurations, functions and behaviours of the different components are integrated into an operational architecture with respect to the global objective.

In essence, the approach proposed in this paper seeks to emulate and not simulate brain function, based on neuroscience results in investigating how the human brain solves problems and shares its function between filtering, processing and analyzing information.

3.2 Human brain – some neuro-scientific considerations

In order to adapt the cognitive processes implied by the proper functioning of a human (including all the decisional layers, from the basic inner functioning of the organism – reflex, unconscious – to the strategic decisions implied by complex societal goals – highly conscious, based on explicit reasoning, learned behavior and selected perception), as they are managed by the human brain to the proper functioning of a large, networked, dynamic enterprise (from real-time decisions of the shop floor machine-control to the strategic decisions of developing new products), as they should be managed by an enterprise control system, some aspects related to a systemic interpretation of the brain should be taken into account.

Systemically speaking, the brain is an extremely large structure, built of networked autonomous subsystems: more than 10^{12} neural "modules", each one having around $10^3 - 10^4$ input-output connections (axons) and around the same number of dendritic and somatic connections – giving a rough approximation of hundreds of trillions of connections at the brain level. This structure is organized following hierarchical principles, in interconnected subnetworks, each of them being able to fulfill specialized functions and to cooperate in order to achieve more complex goals [2]. Some authors are considering that this hierarchy has not a dedicated coordinating level, and that functions are distributed spatially, in different brain regions [23].

Authors as [13] are considering that cognitive functions are fulfilled based on connectivity patterns implying different brain regions, with different specializations. Knowledge management at brain level is based on distribution and parallelism and is determined by the interconnectivity of cortical networks.

In order to design a functional control architecture with functioning similar to the human brain, it is important to devise a set of procedures that allow "processing modules" to incorporate changes, to adapt to the environment, to evaluate results – meaning to allow the system to learn and develop, based on the actual results of the processing.

There are researches [28] mentioning the possibility to develop models capable of dynamic reconfiguration of neural clusters, based on their respective functionalities. A systemic control approach addressing this aspect should consider an agent-based architecture, where the adaptability could be divided both in local integration for agents and in the dynamic reconfiguration mechanism (the Grouping operator) of the architecture, as triggered by some events, either resulting from the environment or from some specified internal factors.

Each cognitive function results from cooperation among different structures and the contribution of processing modules networked in different patterns, thus generating emergent behaviors [1].

All these aspects should be embedded in a systemic characterization of the brain cognitive functions contributing at the definition of the following aspects [10]:

- **The information view**: which are the data to be used (specific source, approach of representation/codification for each architectural level and for each type of problem to be solved);
- **Processing principles**: to be adapted for each type of information, knowledge item and for the description of the (dynamic) evolution; resulting in state trajectories, generated in a multidimensional space, determined by the information view;
- **The recurrent architecture** of the brain – which represents a crucial precondition for the functional integration, determining the systemic view approach.

We are considering that the flexibility and the robustness of the brain, as a system able to process, in an adaptive way, exogenous and endogenous information and knowledge, may be implemented by adapting the context-aware network of networks approach to an agent-based architecture, with reconfigurability capabilities, triggered by asynchronous events.

Each agent should be interpreted from two points of view: the functional one, related to its internal, inherent structure and specialization and the organizational one – related to the actual networking pattern, which reflects the collaborative capabilities. The resulting system is therefore highly flexible and adaptable and presents some characteristics of the matrix-organized enterprises.

The responsibility for solving different kinds of problems is associated with different sets of neural clusters; where one of them has the coordination and the others are associated in a collaborative, flexible network. This functionality may be emulated using a Multi-Agent structure having one coordinating agent and multiple underling associated agents organized in a hierarchical and heterarchical architecture [9].

3.3 Perception – Memory – Learning

The evolution of the human brain is shaped by its history and depends on capabilities of learning and developing successful behaviors facing different problems to be addressed. Actually, problem solving and behavior generation are very closely related concepts, their correlation being performed via a complex system of success evaluation and enhancement.

Our approach is based on the assumption that intelligent behavior results from successfully solving problems. It is a statement that is valid both in the case of living organisms (human brain) and in the case of manufacturing enterprises (control systems). The behaviour efficiency or the degree of intelligence resides in:

- **problem recognition** (correct differentiation between problems with a high degree of similarity): **perception** based on **memorizing** (a-priori models);

- **problem solving** with a minimum resource spending and in an adequate time interval (which will involve at some point prioritization, conflicts and decisions): **behaviour generation**;
- **interpretation of results**: reasoning, learning, memorization.

Perception - Memorization - Learning and Behavior generation (PMLBg) are highly structured, interconnected processes that characterize intelligent behavior and adaptation. They should be a part of every control system that intends to apply human-brain functioning and cognition approaches into the management of a complex, dynamic, evolutive enterprise. Actually, the set of inherently necessary functionalities that have to be embedded in such a control architecture includes:

- Perception – of the real world, or of a problem model
- Modeling: Reality models (patterns)
- Model encapsulation
- Reasoning
- Learning
- Behavior generation – model parametrization and action

The simplified representation of this view is presented in Figure 2, where the module of information processing is the key link between the real world (environment – perceived through sensorial inputs) and the world model on which problem solving (reasoning) is performed. The real world perception function implies modules as inputs, information processing, codification and recovery, thus including reality models building and supporting behavior generation.

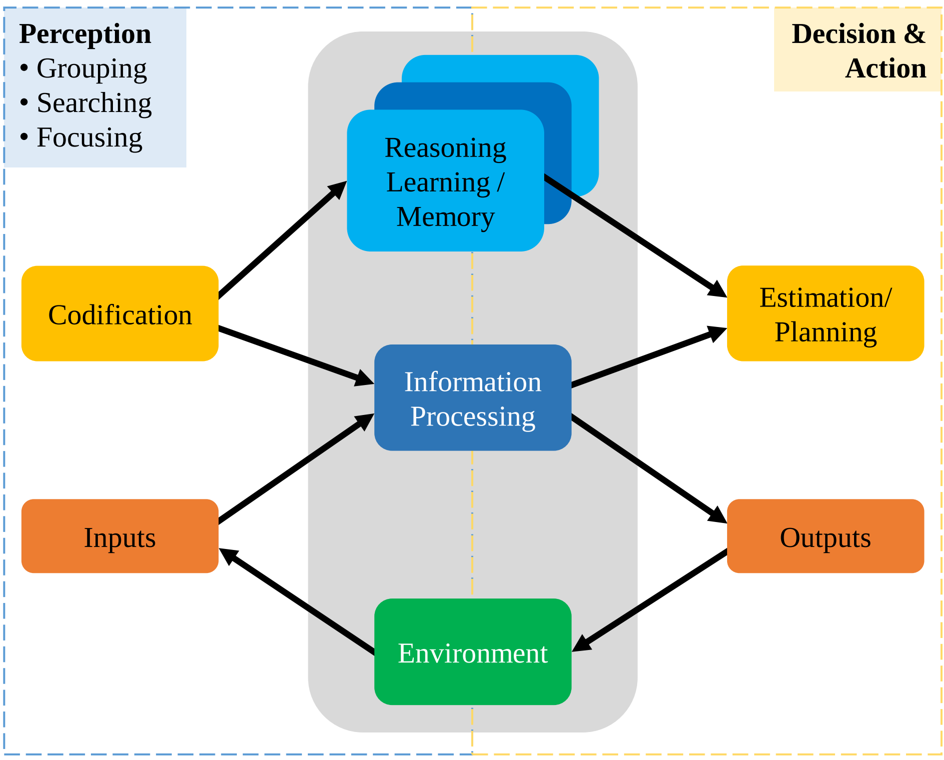

Figure 2: Simplified representation of the cognitive processes.

Given the limited capacity of the brain / control system and the vast amount of data from available environmental inputs it is the place of the perception function to group correlated data, search for necessary information and focus on relevant aspects in order to ensure the efficiency of the global process.

Depending on the external context, on the internal state of the system and on the already memorized and learned models, actions and behavioral models are generated, in planned and ordered sequences of actions, whose intermediate results a-priori estimated, thus supporting necessary decisions.

Deciphering the mechanisms of perception, memorizing, learning, reasoning and behavior implies the understanding of the coordinated and emerging activity of cells, synapses and neural networks of the brain, as well as of the ways in which the four intelligence essential modules (perception, learning, reasoning, behavior generation) are interconnected [8].

There is already a particular interest in identifying how data from the environment is grouped, stored and eventually shared as information and knowledge between different brain regions and for different purposes, provided that decision-making that leads to prioritizing actions and pattern recognition is the field of excellence of cognition.

There are some researches, as [25], which state that the meaning of symbols, which are used in cognitive models, "is associated with extra-linguistic space, with thoughts, emotions, spirit, and meditative state of mind". The representation of meaning is obtained as a result of an evaluation of a (possible very large) set of possibilities.

The problem with complex CPS, such as manufacturing systems, is that they are made up by interconnecting several categories of specific subsystems, which leads to major problems in choosing the appropriate modeling formalities; in fact, hybrid models are often used, whose performance is inherently sub-optimal in relation to the issues addressed at the local level or the interface of (different) models of subsystems with different characteristics, generating a global emergent behavior.

In addition to the characteristics of heterogeneity and geographical distribution, such systems have various levels of dynamics, should operate according to strict requirements of reliability and security, in conditions of uncertainty, rarely repeatable and pose problems whose solutions could be multiple or may not exist.

Therefore, one can speak of a true cognitive approach only in the situation when, in parallel with the control architecture, an adequate modeling formalism exists, which should include both the possibility of pure, quantitative mathematical modeling and logical, qualitative modeling, as well as the integration of uncertainties and degrees of trust through which the information necessary for strategic decisions is usually quantified.

Regarding our approach, it is based on certain perceptual considerations, which will be briefly presented in the next section.

Intelligent CPS represent a concept showing how tight are integrated different physical components with the information and knowledge and how the shaping of this information impacts on the physical part behavior and success.

3.4 Perception-oriented architectural approach for cognitive enterprise

Following the considerations described in [10], a key approach in designing the architecture presented in this paper is the concept of "perception".

The differences between two cognitive systems with the same set of input data and the same set of resources resides in their capacities of rapidly and correctly identifying the pattern of a problem to be solved (existence of "good" – complete and compact reality models), in the case of an already existing solving knowledge or of focusing on relevant information to be correlated and used in generating the solution of a new problem, thus reducing the state space of possible approaches and the number of trials.

Both aspects are related to the concept of perception – of a specific problem or of a situation – and are necessitating the use of operators as "focusing" and "grouping" with respect to information and data. Based on the perception of a situation, the control system may decide either to apply an already known piece of knowledge with an adequate parametrization or to address it as a new problem, thus subsequently applying existing procedures, analyzing and evaluating their results and appropriately combining them in a new piece of knowledge – there two being samples of completely different approaches, necessitating different types of agents and different patterns of networking them.

Even the process of converting useful data in information and knowledge, which necessitates contextualization is perception-dependent, as context is given by the perceived states of respectively environment and system. Moreover, given the huge amount of data available in enterprises of the kind that require a cognitive approach in their control and management, contextualization is a critical-time process, and, consequently, should be designed appropriately.

As mentioned above, problem solving is a reasoning process - but in a complex system, with different levels of granularity, it naturally may have different complexity levels.

The existence of different levels of complexity in solving problems, differentiated by the level of self-awareness in perception and reasoning and the need to identify patterns, learn procedures, generalize, customize, etc. is easily observable through the human behavior, ranging from reflex actions to long term strategies for solving completely new problems.

Our approach addresses basically the following complexity levels:

- **Level 1: Problem solving based on a known (learned) approach:** the problem model is known – part of a library of models/ patterns; perception consists in focusing on and checking the model structure; the context reflects in parametrization; agents that have to participate in the solution and the appropriate networking is established (retrieving / replicating a reasoning model with a different parametrization)
- **Level 2: Solving a new problem by associative reasoning**: decomposition of the problem in known patterns (may exist several ways of decomposing; have to be tested and evaluated); adjusting perception to the similar problem; test relevance; extend perception and retry with similar reasoning (building new knowledge from known sub-patterns).
- **Level 3: Solving a completely new problem – no decomposition could be performed**: basically "trial and error" – implemented by extending perception; grouping and focusing on different channels; test relevance for each channel; generate emergent perception from several channels; construct reasoning; test reasoning (capturing / acquiring new knowledge)

As mentioned above (Section 3.3), problem solving necessitate the pre-existence of models (reality models, world models, problem solving procedures models) and of procedures for generating behaviors, testing results, evaluating results, selecting solutions. For the majority of these models, perception is defined, either as a set of sensorial channels to be used (level 1) or as a set of grouping/ focusing procedures for existing inputs (levels 2 and 3).

In this way there always is a set of information to be acquired (feed-forward loop), whose structure and, possibly, values are anticipated. The gathered information is compared with the anticipated one and the actual result determines the level of problem solving and the next step in the problem solving pattern to be performed (feed-back loop) (Figure 3).

The human brain is able to deal with problems at the level 1 without implying the self-awareness of the subject; these are knowns as reflex behavior and are the result of either a "system initialization" (innate) or of a learned behavior (acquired), for problems that were solved for a given number of times with success (positive reinforcement).

Usually, the innate reflexes are addressing extremely basic functions of the organism and they are not really supposed to be changed. The brain "automatically" adjusts these behaviors to environmental parameters and / or the state of the body. From the manufacturing point of view, such behaviors could embed CNC programs or basic process models. From the perception point of view, there are no "volitional" / self-aware actions to be taken; usually there are embedded sensors that are sending information for local control modules. There is no learning process to be described – the behavior is an embedded algorithm, so as actions are "automatically" taken.

There may be acquired reflexes – as more complex behaviors, that were successfully applied for a certain number of times, so as they were (empirically) proved as solutions for given scenarios. They are applied provided that the problem they serve is properly identified and the focus of the problem solving process is towards this identification.

The trigger between conscious (awareness) and unconscious (un-aware) regime of problem solving may be either the identification of a new problem or the detection of a large difference between anticipated and actual information (the feed-forward/ feed-back loop).

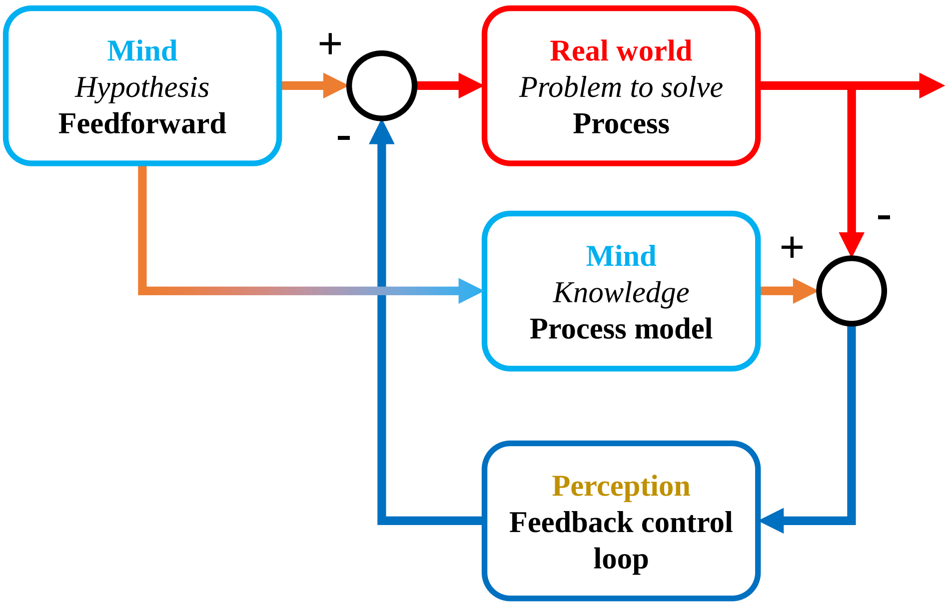

Figure 3: Feed-back and feed-forward loop.

In the aware / conscious regime, the cognitive system takes the control and addresses the problem, usually by associative reasoning and then by trial and error techniques, thus passing from level 1, to level 2 and 3 respectively. Once a new problem is successfully solved, the reasoning path may be memorized (learned) – thus migrating from level 3 to level 2, and, by positive reinforcement (repetition of success) to level 1.

A similar situation may arise for an enterprise with concern to real-time control at the shop-floor level or with any other kind of process that has an appropriate workflow - and which may be considered as an acquired reflex. Once a new problem is detected, new problem-solving mechanisms are triggered, identifying knowledge and knowledge stakeholders, modifying perception parameters, decomposing problems, generating emergent behaviors and evaluating outcomes, until the problem is solved. Then, the problem-solving pattern and problem context model will add to the enterprise experience (learning).

There are some important aspects to be addressed when characterizing a framework for Cognitive Manufacturing Control, as:

- the levels of granularity of perception (from data acquisition towards searching, clustering and structuring data in order to obtain qualitative models)
- the reasoning models (implicit and quantitative - embedded algorithms - explicit and qualitative)
- the learning models / verification and validation of proposed solutions
- behavior generation models

Perception processes are hierarchically organized and the multi-resolutional architecture is based on the generalized operators GFS (Grouping, Focusing attention, combinatorial Search) where the data and information are transformed into attributes with symbolic representation. The reasoning and learning processes are based on semantic representation. Behaviour generation and action planning are based on the inversed generalized operators.

Through the research conducted by our team we tried to identify a number of constituent elements for the development of the design framework for the control system of cognitive manufacturing enterprises, such as the categories of fundamental attributes for differentiating problem solving processes and types of support processes that should be implemented such that the functions of perceptual, reasoning, learning and behavior generation could be performed [8].

Figure 4 is intended to summarize the issues to be addressed in the future for the complete description of the framework. Except for the level of pure reflex - which should be pre-programmed, the architecture is dynamic and problem solutions could migrate between different Problem Solving (PS) levels, according to different attributes as the trust level, self awareness, a.s.o [27].

PS level	Perception	Reasoning	Learning	Action / behavior generation	Processes to be developed
Pure reflex	• non volitional • grouping	implicit	-	• non volitional • atomic	• Parameterization: retrieving required data • Grouping • Consistency check: estimation vs actual result (qualitative)
Acquired reflex	• non volitional • focusing (self awareness) • grouping	implicit	only negative reinforcement	• non volitional • estimation	• Retrieving information • Pattern identification • Focusing
Learned behavior	• volitional • self aware • searching • grouping • focusing	explicit	• volitional (qualitative) • validation	• volitional • planning • milestones • real-time • complex	• Capturing information • Validation
Developed behavior *(associative learning)*	• volitional • re focus	• explicit • trial and error • logical feedback loops	• volitional • positive and negative reinforcement	• volitional • planned • estimated	• Searching for knowledge • Problem decomposition • Access appropriate PS level • Learning • Sharing
New problem	volitional	?	?	?	?

Figure 4: Brief description of the architectural framework components.

Our actual work is focusing on developing the levels of acquired reflex and of learned behavior. For this purpose, out team has developed a hybrid modeling framework, allowing the integration of mathematical models, logical models, uncertainties and degrees of trust and has implemented a software platform allowing the design and evaluation of models that may be used to support the learned behavior approach [22].

4 A software modeling platform to support the development and analysis of cognitive process models

The design of a meta-model with the degree of generality required by the control of an intelligent enterprise is based on the cooperation of specialists with different backgrounds and as such, has to achieve a balance between qualitative and quantitative aspects. Such an enterprise requires training for specialists and testing and evaluation of models. For this purpose we have conceived a software platform allowing this kind of cooperation and which is briefly described in the following.

Managing manufacturing systems involve a continuous process of decision making in which multiple levels of requirements need to be considered. Such decision making problems include:

- how to build the manufacturing line
- how to structure the manufacturing process

- what equipment to purchase
- how to improve the manufacturing architecture and layout
- how to allocate resources and how to schedule tasks

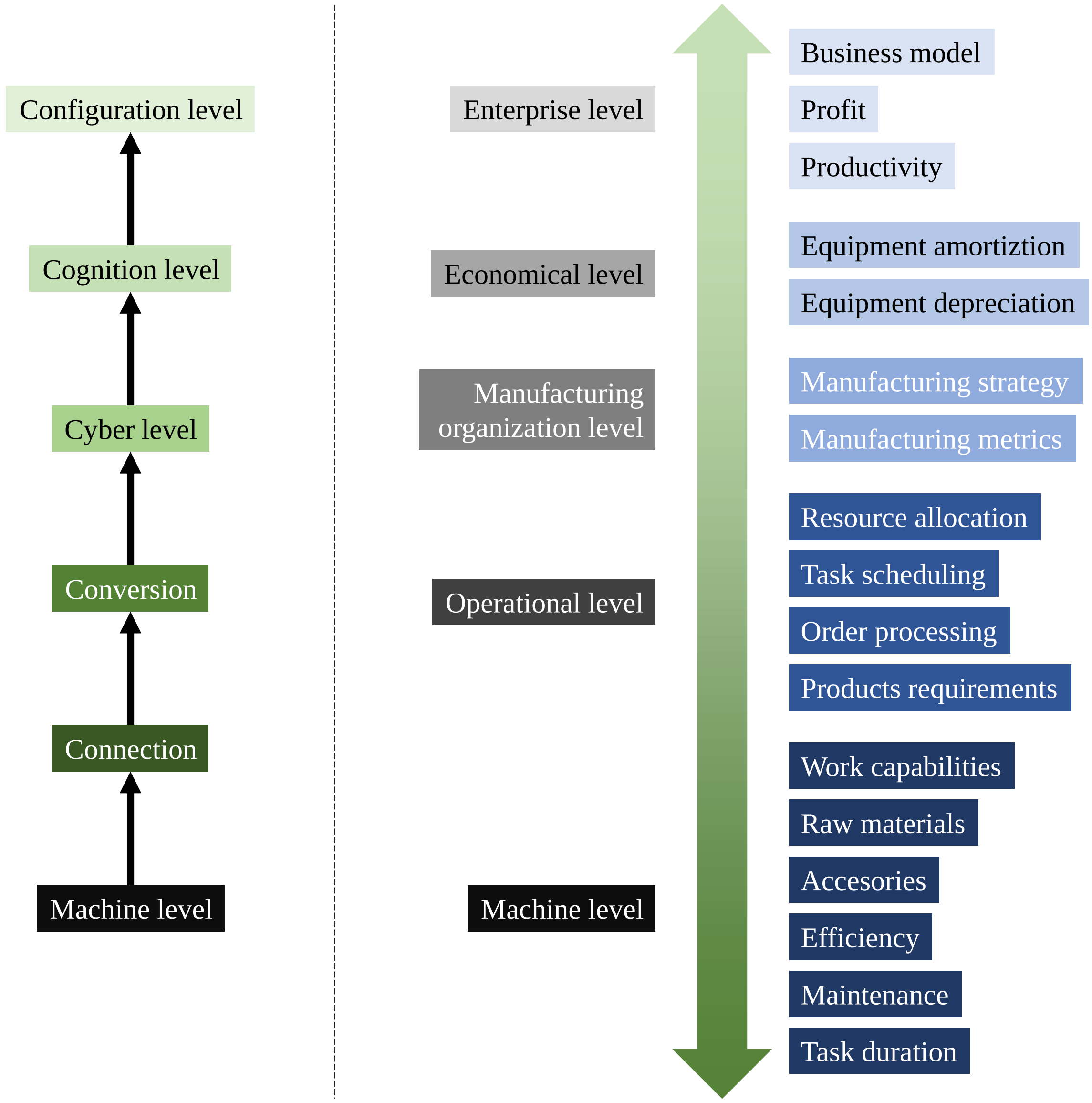

Figure 5: Conceptual map of different levels of requirements that need to be considered when designing and managing a manufacturing system as a parallel to the flow of data in a CPS enabled factory, as identified in [18].

All these choices are considering requirements at all levels of detail, from the enterprise level down to the machine level. In Figure 5 a conceptual map with all the main levels of requirements is presented. This top-down approach must consider a complementary bottom-up one which originates from the data flow topology in a factory, as identified in [18]. At the top, at the enterprise level there are strategic requirements shaped by the business model adopted and the foreseen productivity and profit. Further, there are the economical requirements which are closely related to the accounting approach like what is the equipment amortization strategy and how the equipment depreciation affects the manufacturing process. Additionally, the strategy adopted in organizing the manufacturing has complex implications in achieving an optimal matching between tasks and resources and the metrics defined for assessing the optimality. The operational level brings specific requirements in terms of task scheduling and resource allocation which have to be performed considering the specificities of the products from the received orders. At the bottom, at the machine level the requirements are rather technical and technological and include machine specifications and characteristics and mandatory measures to ensure optimal machine operation and increased availability.

The decision making in such a diverse and heterogeneous context requires specialized modeling formalisms and tools which simultaneously consider all levels of requirements and detail. Such tools must reach beyond a limited numerical approach and to provide a flexible, universal, modular and intuitive modeling formalism and language, suitable in diverse domains of expertise.

In this respect, we are developing a hybrid modeling formalism and software platform that are considering all the above mentioned objectives, which combine in a unified approach three formal elements: relational models providing rule – based inference mechanisms [3, 4] trust factors for describing uncertainties and numerical parameters for considering precise information.

The formalism is considering modelling environments including multiple abstract entities (models) that are interacting. The environment is abstracting the behaviour of the entire manufacturing context while each model is abstracting the behaviour of any real entity (equipment, workflows, systems, constraints, etc.). The models contain several types of resources: input, output and internal parameters and attributes. The behaviour of each entity is defined and analyzed considering its logical structure using logical predicates with attached trust factors for describing behavioural uncertainties.

The formalism intends to bring a balance between the structural component of the model, based on behavioral characteristics and adapted to reasoning and the numerical component, of mathematical calculation, which generates the actual outputs of the system. It aims to preserve the properties of compositionality that will allow the construction of models with a high degree of heterogeneity and, consequently, with the capacity of dynamic reconfiguration.

Given the characteristics of complex systems, in the Cyber-Physical Systems paradigm, it is assumed that the component subsystems will be modeled based on the experiences, knowledge and objectives of specialists with different backgrounds, as their natures will be different. The models will be built concurrently and the analysis of the global behavior, the coherence of the functioning specifications and the interactions between the components of the system represent aspects that such a formalism must be able to clearly highlight.

In addition, it is important for the formalism to have significant semantics - to highlight and understand the structure and functionality of the complex system and its components, to allow flexibility and reconfigurability of the global system based on its component models and interaction. It allows the parameterization and quantification of the models so that various variants of operation scenarios can be compared and is versatile enough to highlight all the relevant particularities of the manufacturing system.

This approach provides a flexible manner to describe the logical and behavioral structure of a complex manufacturing context where multiple levels of requirements are simultaneously considered. The modeling platform assists designers and engineers during the learning process meant to built intuition and knowledge, during concept and design evaluation and operational decision making.

In Figure 6 and Figure 7 is depicted an application scenario that is implemented in the modeling platform where the aim is to define and analyze the behavior of a flexible manufacturing system which includes three processing centers. The system can produce four types of products which are defined using four different workflows including multiple tasks. Each processing center can execute part of the tasks with different time and resource cost.

The modeling is simultaneously considering multiple factors that are influencing the operation of the manufacturing process:

- How the machine productivity is affected by economical, technological and operational requirements and factors
- How the load of each machine is affected by operational parameters (the length of the input / output product queues) and its productivity
- How the resource allocation approach and the requirements of the workflows are correlated with the load of the machines

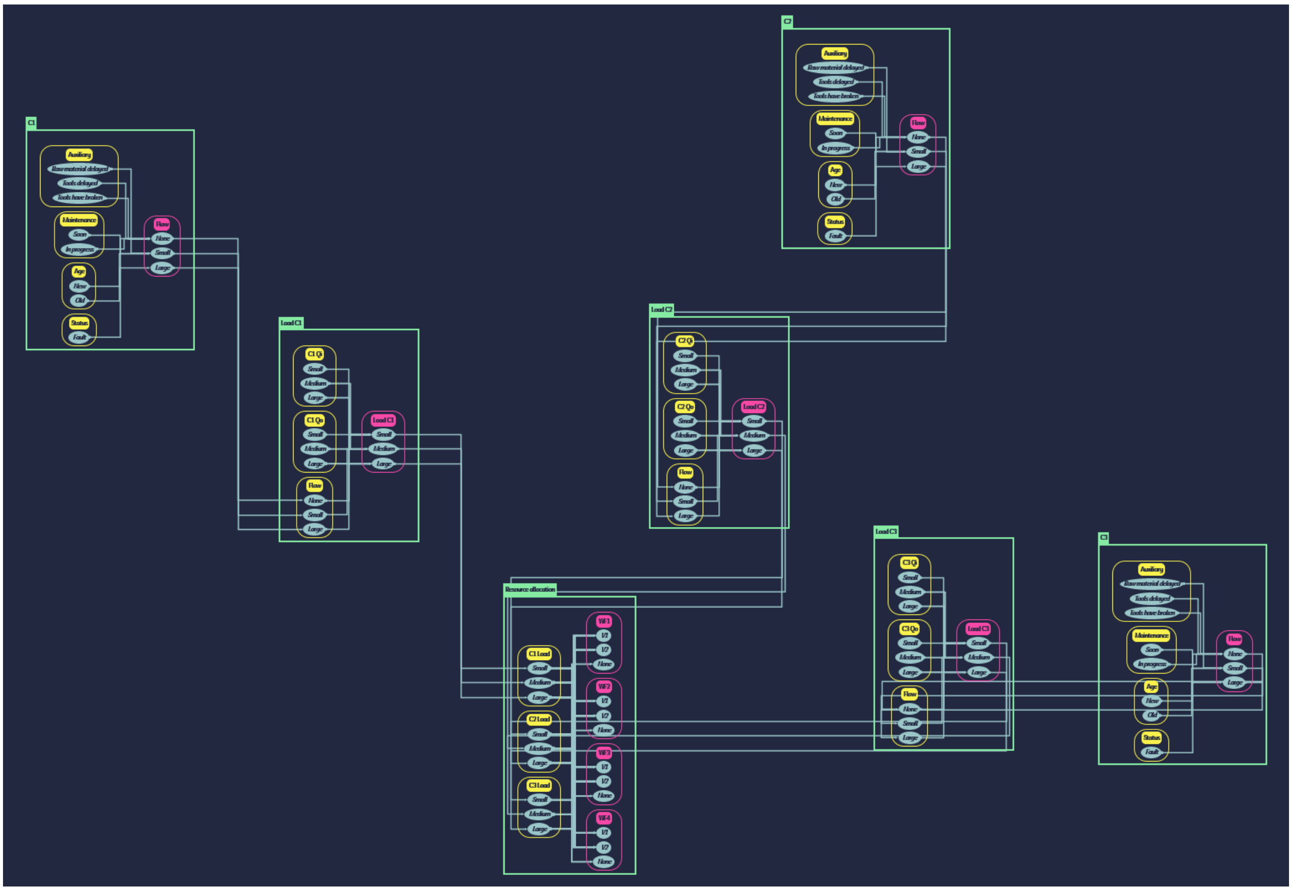

Figure 6: Using the modelling platform to define and analyze the behaviour of a complex manufacturing scenario.

This modelling approach is useful for designers and engineers for implementing and testing various context scenarios, behaviours and strategies in order to build intuition and knowledge for this particular manufacturing system. Additionally, the model can be used in decision making problems like generating the optimal resource allocation strategies or assessing if new tasks can be executed based on the current system load. The platform can also assist the process of iteratively building a knowledge database useful in matching the particularities of future applications with pre-designed solutions. This platform has the capability to support the design and test of a structured architecture that may generate different behaviours by combining different sets of models through given problem solving requirements, emulating the cluster-oriented behaviour of the human brain and helping in its understanding.

5 Conclusions

The paper opens some new research directions in relation to the enterprise of the future, which is perceived as a complex and dynamic system with capabilities to adapt to environment by perception, learning and decisions for an optimal behavior.

The fundamental contributions of this paper are:

- Identifying the classes of systems that can benefit from the neuro-inspired cognitive control approach (Section 3.1).
- The modeling approach to be used in the design of a cognitive control system as a parallel with the brain system (Section 3.2) with emphasis on the systemic overview.
- The problem solving principle within this type of system, based on the Perception - Memory - Learning and Behavior Generation mechanism and subsequent architecture (Sections 3.3 - 3.4).

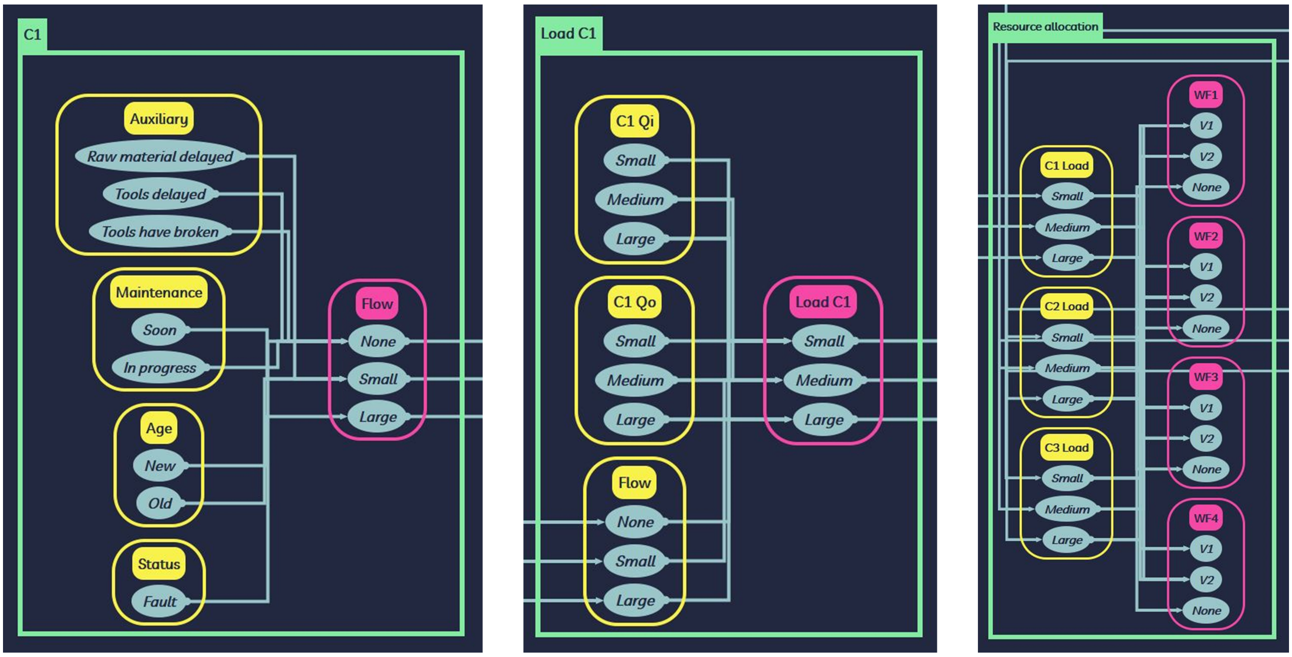

Figure 7: Details of models from the platform abstracting the three types of entities in the scenario.

- Design and implementation of a software platform to test and combine system models that are conceived based on our modeling approach and problem solving mechanism (Section 4).

Derived from its similarity with human adaptive abilities, the evolution of the next generation of intelligent enterprises will be more and more based on its cognitive abilities, as the human brain.

We should understand more about perception, learning and action from cognitive systems, to be able to design and implement a new generation of socio-technical systems as an autonomous enterprises.

The complexity and the diversity of problems which arise in the field of structural - functional organization of the enterprise of the future request a new systemic vision, based on the cooperation and collaboration of neural clusters with multiple complex problem solving abilities. Hierarchical and heterarchical organization of clusterized functional structures will allow them to associate and cooperate in various contexts, as requested by the particularities of problems to be solved.

Autonomy, dynamical reconfiguration, auto-organization and the ability to adapt to various requests and endogen and exogenous conditions determined by specificity of digital cognitive enterprises may be implemented using the human brain functional organization system.

The generic platform conceived and developed for the design and analysis of complex systems with real adaptive capabilities allows, by a warehouse of models (algebraic, relational and logical) the successful implementation of specific functions as perception, learning, planning and adaptation. By this paper we are trying to open a discussion about the possibility to organize the future enterprise as a complex system that includes some important attributes of the human brain as the ability to capture attributes. This means a new research direction to create dynamical systems with real capabilities like the human being.

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Author contributions

The authors contributed equally to this work.

Conflict of interest

The authors declare no conflict of interest.

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