On the architecture scheduling problem of Industry 4.0

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***Abstract*—The recently emerged Fourth Industrial Revolution (Industry 4.0) is characterised by the introduction of the new Cyber-Physical System (CPS) concepts and the Internet of Things (IoT) paradigm. These new collaborating computational entities offer a broad range of opportunity to consider with a different perspective. One of the perennial problems of the manufacturing operation is the scheduling problem of typical job-shop manufacturing systems. Starting from a comparison with the typical architecture of an operating systems scheduler module, we introduce a new manufacturing scheduling architecture. Overcoming the typical Full-Hierarchical configuration defined in the ANSI/ISA 95 in favour of a Semi-Heterarchical one, the introduced scheduling architecture leads to a mixture of proactive and reactive approach to the Job-shop Scheduling Problem (JSP), taking advantage from both the common decentralised and the centralised methodology.**

Keywords*— *Industry 4.0; Cyber-Physical System (CPS); Job-Shop Scheduling Problem; Manufacturing System; System of Systems.

I. INTRODUCTION

The previous industrial revolutions were principally characterised by advanced in the technology field. The recently emerged Fourth Industrial Revolution (Industry 4.0), instead, is characterised by the presence of new technologies which, thanks to their interconnection ability and the following combination of the physical and digital world, allow an evolution in productive logics and architectures. As well as every past industrial revolution introduced a new enabling technology, the Fourth Industrial Revolution is characterised by the introduction of the Cyber-Physical Systems (CPS) and Internet of Things (IoT) paradigm [1]–[4].

The CPSs are systems in which the “cyber” part, sum of computational and communication capabilities, and the physical part are tightly integrated either as project that as operations. Said differently, the CPS term refers to a mechatronic system that interacts continuously with a system composed of physical elements, each with its computation capacity. This brings to a collaborative system of computational elements linked in an inter-networking of physical and embedded devices, known as Internet of Things.

In the manufacturing paradigm, the current state of the hierarchical plant organisation is defined in ANSI/ISA 95 [Fig. 1]. In particular, four different main component of this hierarchical domain are distinguished: Enterprise Resource Planning systems (ERP), Manufacturing Execution System (MES), PLC/SCADA systems demanded to the Process Control activity and Device itself [5]. In this plant organisation, the decisions taken in the upper levels are sent to lower level, and each decision-making problem is solved separately and independently. The decisions adopted at every level may have different time horizon (long, medium or short periods), complexity and objectives. In the ERP level, for example, the supply chain configuration has a time horizon of weeks, while in the Process Control level, the scheduling has a shorter time horizon with a focus on the dynamic performance of the process. However, the appointed ANSI/ISA 95 limits its applicability to the definition of the different typology of information exchanged between the described levels, without any consideration of the communication standard to be used [6]. In this sense, an important framework that covers these specifications is the OPC Unified Architecture, whose purpose is to create a communication platform between the MES and the PLC/SCADA, independent from manufacturer vendors, operating systems and programming languages used [7].

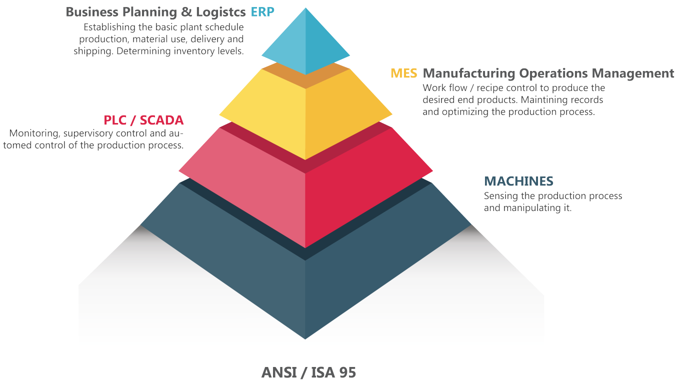

Fig. 1 – The ANSI/ISA 95 Hierarchical Architecture

The scheduling and processes production control have a particular influence on the performance of the manufacturing system. In this perspective, with the application of the hierarchical architecture proposed by ANSI/ISA 95 standard, two different problems arise. Firstly, most real manufacturing systems are too complex to be modelled and solved by the major known solvers (because, also in the simplest case, it represents an NP-hard problem) even if the algorithmic power of these programs improve every day [8]. Secondly, the breakdown between the ERP System (responsible for the manufacturing planning) and the MES System (responsible for the processes control on an operational level) create a situation

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in which, also if the best mathematical optimization is found in the ERP level, it may be not optimally performed for the specific state of the shop floor (i.e., an unexpected delay during the processing phase, a machine failure, etc.) [9]. In common practice, this problem is solved performing only a basic schedule at the ERP level, demanding the shop floor control by straightforward and static dispatching rules at the MES level. This practice allows a robust but not optimal schedule of the production system [9]-[11].

Clarifying, in the traditional vision, the ERP System solves the production planning with a proactive approach, establishing what and how to produce [12]. It solves the ample sequencing and the scheduling problems, defining a plan with the exact dates for the start and end of every operation. However, a proactive approach allows a robust scheduling when the uncertainty can be quantified in some way (e.g., by introducing the "idle times" between jobs) [13]. This approach may lead to a robust schedule but with the risk of a low machine utilisation if, as an example, the idle times chosen are too conservative [14].

At this regard, the introduction of the CPSs systems and the IoT infrastructure at the shop floor open to a broad range of opportunity to consider with a different perspective: taxonomy, design, maintenance, supply chain management, operating rules and process planning [15], [16].

In particular, in an entirely decentralised architecture, the CPSs may be able to solve the production planning with a reactive approach: every CPS may react to the actual occurrence and situations with a decentralised and autonomously decision. However, this problem results in an additional optimisation problem (e.g., the choice of the best rule for every decision) and may not represents the best solution for the entire manufacturing plant [17], [18].

Instead, the aim of this paper is to overcome the full Hierarchical structure of the above-mentioned ANSI/ISA 95 in favour of a Semi-Heterarchical ones, in which the ERP system is still present (for all the pro that its introduction in the plant implies) and the MES evolves to a System of Interconnected Systems (i.e., CPSs). This Semi-Heterarchical structure allows solving the production planning with a mixture of proactive and reactive approach, taking advantage from both decentralised (represented from the autonomous CPSs) and the centralised architecture (of full Hierarchical structure).

In the following Section, this architecture is introduced with a parallel between the manufacturing job-shop scheduling problem versus the Computer Processing Units scheduling, due to similarities that the scheduling problem assumes in the Fourth Industrial Revolution. In Section 3, instead, a real implementation of this architecture is shown and discussed.

II. The New Industry 4.0 Scheduling Architecture

In the manufacturing and operative research, there is a wide presence of paper and solution on how a scheduling problem may be solved [19]. In according with Graves S., the "production scheduling may be defined as the allocation of available production resources over time to best satisfy some set of criteria" [20]. More precisely, the scheduling problem have to determine when and where to perform a set of elementary job or tasks, making a trade-off between early and late completion of a task and between building an extensive inventory for an item with a frequent production changeover. At this regard, different classifications for each type of production systems can be provided. Ribas et al. [21] present an extensive review of the papers about the Flow Shop scheduling problems with particular attention to the Hybrid Flow Shop systems. They categorised the problem into Parallel Machine Scheduling, in which the scheduler algorithm is responsible for allocating the job to identical machines, and Flow Shop Scheduling in which the main responsibility of the scheduler is to choose the production sequence of the jobs, according to the technology constraints [22], [23].

The Job-shop Scheduling Problem (JSP), instead, may be divided into two categories: offline JSP, in which all the jobs to schedule are concurrently known from the scheduler, and online JSP, in which the jobs may arrive one by one, in function of particular production needs [24]. A standard JSP is composed of n jobs to be processed on m different machines. Each job may consist of k elementary operation to be processed by a given technological sequence (e.g., with a precedence diagram). The pre-emption during the execution of an elementary operation and the overlapping is not allowed, while the goal is to minimise the makespan [25]. As known, the JSP is NP combinatorial optimisation (NP-hard) problem and, in the scientific literature, there is a wide number of research focused on how to find the optimal solution of this problem (through linear programming, genetic algorithm or other heuristics) [26]. However, as said above, in an Industry 4.0 environment the scheduling should deal with a more high-dynamic environment which opens to a combination of proactive and reactive scheduling approach. In this context, this paper wants to introduce a new architectural approach, overcoming a Full Hierarchical approach to Semi-Heterarchical ones.

For the similarities between the scheduling operations of a Job-Shops Industry 4.0 high-dynamic environment and the scheduling operations of an Operating Systems, we analysed the experience gained from the Information Technology (IT) field during the past years in order to inspire a new architectural framework also for the industrial world.

i. Operative System Scheduling Architecture

Inside operating systems, the scheduler represents a module or a set of modules that choose and select the next jobs or tasks to be processed by a particular Processing Unit. Usually, the operating systems present up to three distinct scheduler modules: a long-term scheduler (also known as admission scheduler), a medium-term scheduler, and a short-term scheduler [27]. The name of these scheduler modules suggests the relative frequency wherewith their function is performed. However, it should be not confused with the common industrial acceptation of it, as it will be more clearly forward.

The Long-Term Scheduler module of the operating system, or the admission scheduler, as suggested by the name, decides which jobs or tasks may be added to the "ready queue", the main memory. In this sense, it dictates what jobs are to run on the system, controlling the degree of multiprogramming. This module is responsible for the typology equilibrium of the load (e.g., it should create an optimum combination of processes that are CPU-Bound or I/O-Bound). Instead, the medium-term scheduler is able to temporarily switch out jobs and tasks, which has not been active for a bit of time or with a low priority, from the ready queue to a secondary memory (e.g., a hard disk drive). In its operations, it tries to carry out a sort of "local balancing" of the tasks, avoiding the processing unit stuck on a particular job, swapping the process back in the ready queue once more memory or processing capacity is available. Lastly, the short-term scheduler is the latter phase of the operating system scheduling module. It decides what is the jobs or tasks in the ready queue to be executed by the Processing Unit. This module can be preemptive which means that it is able to forcibly remove working processes from the Processing Unit, deciding to allocate this Unit to a different jobs or tasks [27]. In [Fig. 2] the described Operating System modules are schematized.

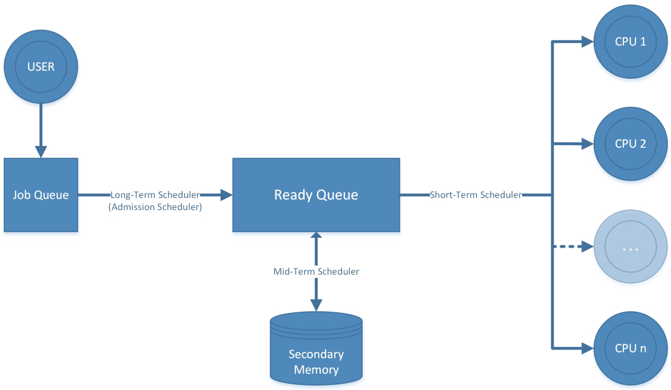

Fig. 2 - Operating System Scheduler

Summarizing, the operating system scheduler is organized in three different level: a sort of admission level, in which the jobs to be executed are selected but not sequenced, a mid-term level, in which the jobs list is locally optimized, and a short-term one, that decided who is the next jobs to be executed and on which Processing Unit.

ii. The Manufacturing Semi-Heterarchical Scheduling Architecture

In manufacturing system control there is a hierarchical organisation, in which the ERP system define the Master Production Schedule (MPS) and the Material Requirements Planning (MRP), releasing the list of the orders to be produced in the next plant shift work. These orders are typically sequenced and scheduled, with a complete routing and production sequence for each item and a machine loading plan for each machine and workers in the plant. During the shift work, the MES is responsible for executing the received scheduled activities, loading the appropriate part-program on the PLC/SCADA and collecting all the error, data and resources check of the production processes. Only at the end of the shift work and taking into account the production data received from the MES System, the ERP is able to reschedule all the not completed and not compliant order, maybe for a particular machine failure or a missed raw material from the logistic systems. In this traditional architecture, the actual hierarchical architecture of a manufacturing plant shows its rigidity. Its ability to react to a problem is limited only to some predefined and basic rules that an advanced MES Systems may have.

The real innovation of the introduction of the CPSs and IoT concepts inside the Shop Floor it is not only to collect and analyse production data from the sensors but their interconnection ability for instantly communicating between them.

In this context, a new architecture with a different approach to the JSP of an Industry 4.0 environment is introduced [Fig. 3]. Like the above-described scheduling modules of operating systems, we may identify three different frameworks also in the manufacturing reality. Firstly, the advantages allowed from the presence of an ERP System are relevant for the competitiveness and the robustness of the actual manufacturing industries. For this reason, the ERP System will still represent the strategic vision of a manufacturing company. However, in the new architecture, the ERP level is only responsible for the MPS and MRP, just releasing all the order to be produced in the next shift work. In this vision, the ERP will no longer define the sequencing and the routing of a particular set of jobs. It will only define and release to the subsequent level, a sort of ready queue of jobs to be produced. Every job will have a complete knowledge of its technological sequence (e.g., every job knowns its technological precedence diagram) without a defined machine loading plane.

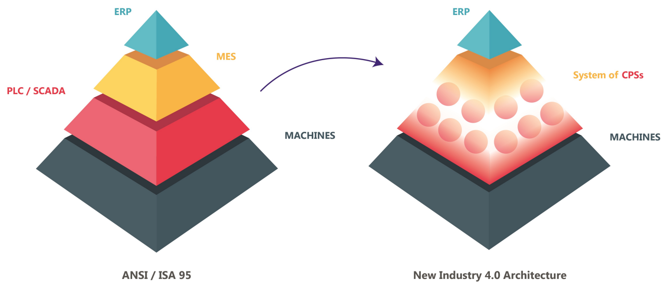

Fig. 3 – New Industry 4.0 Architecture

At this stage, as the operating system scheduler, a ready queue of all the jobs to be completed is built and transferred to the next scheduling level. It should be noted that this architecture allows to constantly update the ready queue of jobs to be produced, avoiding to wait for the next shift work. At this point, in the scheduler of the operating system, a mid-term scheduler, with the purpose of local optimisation, is expected. In an industrial context, instead, all the CPSs share the knowledge of the jobs in the ready queue and locally cooperate to schedule each task to every machine. This second framework represents a novel MES System, a System of Systems composed of all the interconnected CPSs. From the ready queue, the CPSs cooperate in defining the production sequences of all the jobs admitted in the manufacture systems. The major advantage of this approach consists in the best knowledge of the production status. The novel System of CPSs know and estimate better than the ERP the production state and may react faster to every problem that may occur during the production. In addition, it is not bonded to a particular production sequence. This new framework knows the technological constraints of every job in the ready queue and, depending on the actual production condition (i.e., the machines saturation, machine health state, etc.), schedules a particular task to a machine instead of another, using the possible technological solution as a degree of freedom.

Respect to the operating scheduling system modules, the second framework in the manufacturing context is much more important and essential. In the operating systems, in fact, it may be present or not. In this architecture, instead, it represents the system with the ability to select and allocate every job to a machine. The reason is trivial: in the operating systems, the scheduling is an easier problem because the processing units are all able to complete the same set of tasks. They only show an overload problem, and the mid-term scheduler tries to balance the workload locally. In a manufacturing environment, instead, every machine is able to complete only a set of possible tasks and cannot do every kind of operation (also if, for the mechanic industry, the CNC machines are able to fulfil a wide set of different tasks). This adds a degree of freedom to the scheduling problem of this second framework: it can establish not only the production sequence but also use a different technology process for the same items, always respecting any technology constraints (e.g., it is possible to create a hole, not only on a drill but also with a milling machine or with a lathe if the hole is axial symmetrical). Of course, every operation will have a different cost and tolerance if it will be produced on a machine instead of another. In this sense, the System of CPSs may cooperate to find the scheduling that better maximise an appropriate objective function.

Summarizing, the Systems of CPSs virtually represents the second framework of the plant architecture, in which every job in the ready queue is allocated to a selected machine. The last level, instead, is represented by the CPS itself taken individually. The CPS, in fact, it is not only able to communicate with the other CPSs but has own computational capability. At the machine level, the CPS is able to evaluate if the selected task is appropriate for the machine it represents. As a matter of fact, with the help of a prognostics algorithm, it may estimate its health state before accepting the selected task, deciding autonomously if the failure probability or the estimated tolerance of the next scheduled workload is acceptable. In this sense, the CPS knows the status of the machine and has the responsibility to accept the assigned job from the previous framework also by completing only some tasks of it. As an example, in a mechanical production system, every item to be produced own one or more processing card. Each processing card represents one of the possible production cycles, according to the technological constraints. As known from the classical mechanical literature, a production cycle is composed of different phases that represents a set of procedure completed on a specific machine with or without disassembling and repositioning the workpiece (e.g., turning phase, milling phase, etc.). Consecutively, each phase may be decomposed in several sub-phases that represent a set of elementary operation completed on the same operating machine and with the same positioning of the workpiece. In this sense, a sub-phase represents the indivisible task to complete on the same machine. As said, then, the CPS evaluates if the machine it represents can fulfil the full job received from the second framework or only with some sub-phases of it. In this way, with a better knowledge of the machine state, the last framework of the proposed architecture is able to decide and schedule the sub-phases to be completed on the monitored machine, eventually postponing to the upper level the sub-phase that cannot be safely completed on the machine. The complete proposed architecture scheduler system is summarised in [Fig. 4].

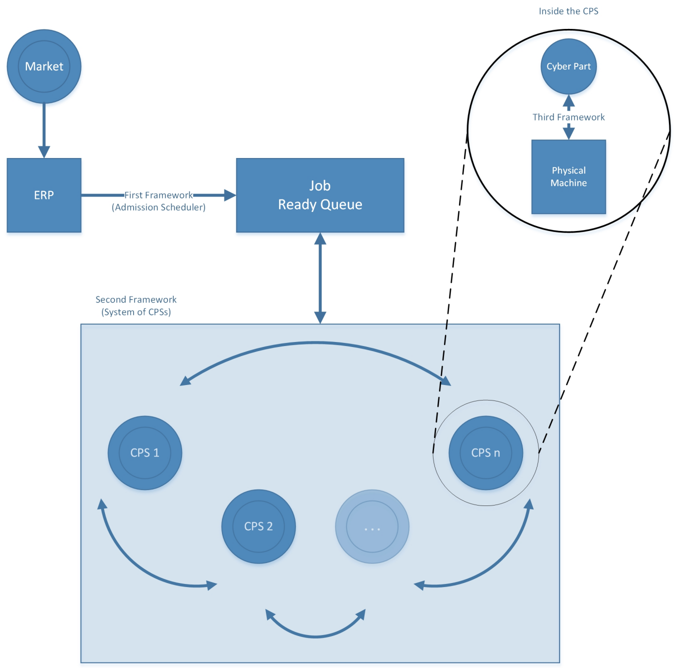

Fig. 4 – The proposed scheduling architecture

III. A System of CPSs: the new MES

In the scheduling architecture introduced above, the most relevant framework is represented by the Systems of CPSs (the second framework). This framework allows overcoming the full Hierarchical ANSI/95 architecture with Semi-Heterarchical ones in which the MES and PLC/SCADA levels are indistinguishable. The ensemble of CPSs cooperates to find the best optimal solution in function of the predefined objective function or behaviour.

With the aim of showing the feasibility of this framework, a prototype of a novel Cyber-Physical Logistic Systems (CPLS) was built in order to simulate the material handling problem of a typical job-shop plant [Fig. 5].

It consists of four processing stations, three of them configured as manual Assembling Stations and the other as an interchange station within the warehouse. The item to be produced is a personalised household product (a picture frame). The stations are connected to an automatic conveyor belt with a carriage release system, designed to handle various carriages with the raw or work-in-progress (WIP) material. For our aim, the precedence diagrams of the produced items are fixed, a priori knew and composed of twelve phases, as showed in [Fig. 6].

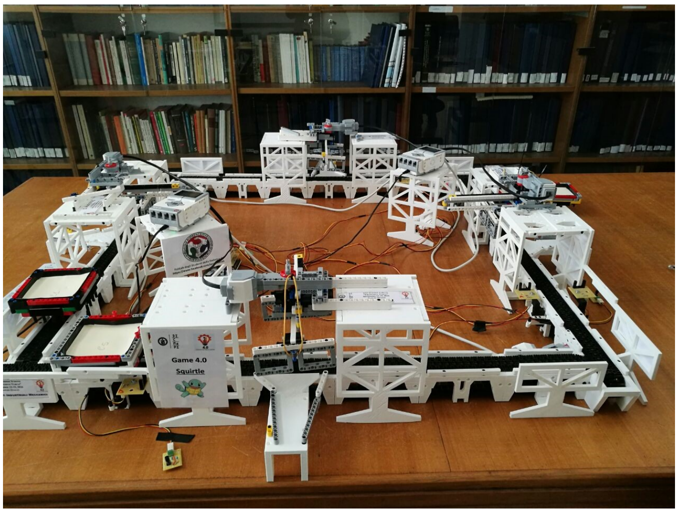

Fig. 5 – The Cyber-Physical Logistic Systems

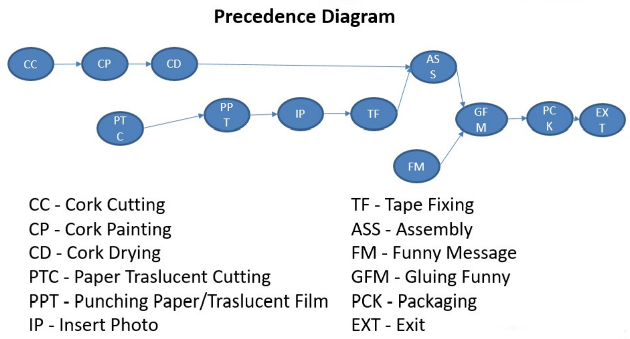

Fig. 6 – Precedence Diagram of the Picture Frame

In order to analyse the scheduling performance of the previous Full Hierarchical architecture with the Semi-Heterarchical ones introduced, the CPLS prototype is designed for operating under two different decision-making logics:

- Centralized Logistics System (CLS), in which the output of the ERP System is the complete Production Cycle with a detailed Scheduling and Routing of every machines and item to be produced;
- The New Introduced Scheduling Architecture, where the ERP System only release the Jobs to be produced, demanding to the System of CPSs the definition of the detailed Scheduling and Routing with a personal decisional autonomy and compliant with the Industry 4.0 paradigm.

Obviously, every Processing Station represents a Cyber-Physical Systems with its autonomous decision capability (for the third framework) and a cooperation ability (for the second framework). Instead, the ERP System is represented by an individual framework in a Personal Computer with the responsibility to release the jobs in the “Ready Queue” of the System of CPSs. Every time the jobs reach this queue, the CPSs starts to cooperate for scheduling the jobs, ensuring the adaptively of the Production System. From an operating and practical point of view, the action of the second scheduling framework (System of CPSs) is triggered by a status change in the system. In our context, we identified several situations that trigger the scheduling activity of the second framework:

- The admission of a job in the ready queue from the ERP System (i.e., when the Fist Framework admit jobs in the Ready Queue);
- The completion of a job by a Processing Assembling machine (i.e., when the Third Framework of a CPS communicate the conclusion of an assigned task);
- A change in the Ready Queue subsequent to the job allocation to a particular CPS (i.e. when the Third Framework of a CPS communicate the complete acceptation of the received job);
- The completion of an item and the subsequent exit from the Ready Queue;
- A change in the system configuration, due to a not expected machine failure or due to the introduction of a repaired processing machine;
- A not compliant item to be reworked;

In order to show the capabilities and the performance of the introduced Scheduling Architecture, we conducted a real simulation of the CPLS prototype under two different decision-making logic, involving four different prototypes and four different teams of workers. Each team was composed of seven doctorates without any previous experience in these manufacturing environments. The experiment was divided into two phases: one is conducted with the CLS decision-making logic while the other one with the introduced Semi-Heterarchical architecture. For every test, the quantity and the typology of the released orders were fixed. However, in the CLS round the ERP System released the detailed centrally optimised Scheduling and Routing of every machine while, in the Semi-Heterarchical round, the ERP released only the Jobs to be produced in the Ready Queue, demanding to the System of CPSs the definition of the detailed Scheduling and Routing plan. To compare the performance of the experiments we identified two parameters to be monitored: the lead time of every job and the utilisation of every processing machines. In our case, the lead time represents the time between the introduction of the order in the ready queue and the exit through the warehouse station. The machine utilisation, instead, represents the fraction of time a workstation is not idle for lack of parts. This includes the fraction of time the workstation is working on parts and is unable to work on them due to machine failure, setup or other detractors.

Considering, in a first time, the lead time and, in a second time, the machine utilisation as the response variable, we analysed the appointed data through the ANalysis Of VAriance (ANOVA) in order to show the significance of the architecture choice on this parameters.

Starting from the bottom of the ANOVA results for the Production Lead Time response variable in [Fig. 7], the Error, Iteration factor and the Experiment Iteration pass the null hypothesis of the Fischer test, ensuring and confirming the significance of the Industrial Architecture factor on the Production Lead Time.

Factor Information

Factor	Type	Levels	Values
Industrial Architecture	Fixed	2	1; 2
Experiment	Fixed	4	1; 2; 3; 4

Analysis of Variance

Source	DF	Seq SS	Seq MS	F-Value	P-Value
Industrial Architecture	1	30,997	30,9974	17,90	0,000
Experiment	3	7,108	2,3694	1,37	0,256
Industrial Architecture*Experiment	3	2,750	0,9167	0,53	0,663
Error	112	193,969	1,7319		
Total	119	234,824			

Fig. 7 – Two-way ANOVA for Production Lead Time versus Industrial Architecture and Experiment

We may conclude, with a very high-level of confidence, that the Semi-Heterarchical architecture decreases significantly (about the 15 %) the Production Lead Time [Fig. 8].

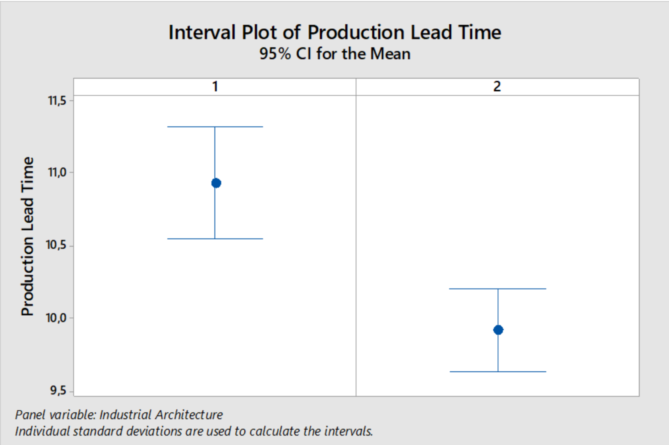

Fig. 8 – Interval Plot of the Production Lead Time for the CLS architecture (1) and the Semi-Heterarchical ones (2)

Repeating the same ANOVA analysis for the Machine Utilization response variable [Fig. 9], it is showed that the significance of the Industrial Architecture factor is important also for the Machine Utilization parameters.

Factor Information

Factor	Type	Levels	Values
Industrial Architecture	Fixed	2	1; 2
Machine	Fixed	3	1; 2; 3
Experiment	Fixed	4	1; 2; 3; 4

Analysis of Variance

Source	DF	Seq SS	Seq MS	F-Value	P-Value
Industrial Architecture	1	857,09	857,091	41,97	0,000
Machine	2	28,33	14,165	0,69	0,513
Experiment	3	16,00	5,333	0,26	0,852
Error	17	347,18	20,422		
Total	23	1248,60			

Fig. 9 – Two-way ANOVA for Machine Utilization versus Industrial Architecture, Machine Typology and Experiment

Also in this case, the choice of a Semi-Heterarchical architecture instead of a Full Hierarchical one shows a higher Machine Utilization (about 20 %) of the processing machine, independently of the machine typology [Fig. 10].

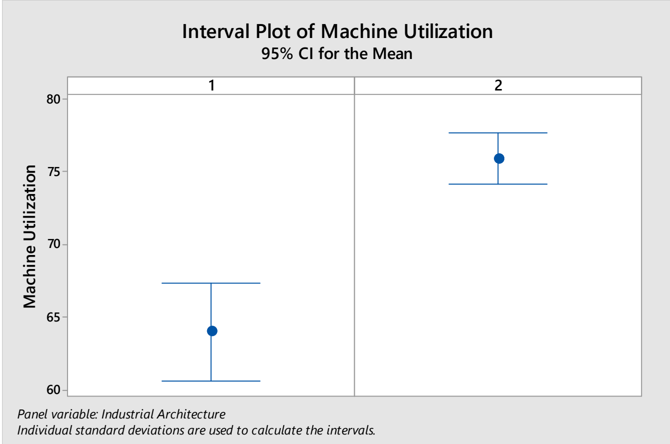

Fig. 10 – Interval Plot of the Machine Utilization for the CLS architecture (1) and the Semi-Heterarchical ones (2)

IV. Conclusions

The approach of the introduced architecture leads to a mixture of proactive and reactive approach, taking advantage of both the decentralised and the centralised approach. In this sense, the resulting scheduling is more robust and resilient with respect to the ones obtained with a full Hierarchical architecture. The major contribution of the introduced Semi-Heterarchical structure is to be found in dividing the unique scheduling problem of a typical job-shop into three simpler scheduling problems, one for each introduced framework. In this way, the ERP solves the first problem, with a universal but approximate knowledge of the production system. Thanks to its ability and feature, it is also able to interact with human pursuing their strategic production vision, establishing the jobs to be admitted in a sort of “Jobs Ready Queue” that will hold all the order admitted to the production. The Sequencing and the detailed Production Sequence, instead, is solved in a second level, with the newly introduced System of CPSs: the new integrated MES System of the plant. The major advantage of this System of CPSs is the better knowing that every CPS has of itself and of the production status. In fact, the rigidity of a Full-Hierarchical architecture is represented by the limited decision autonomy of the actual MES System (usually consisting of simple rules to be executed and in a consumptive role of the production progress). The last problem, instead, is solved internally at the CPS and the machine itself. Only the CPS knew the current state of a monitored machine, and it may take the final decision on what tasks of the received jobs are safe to be produced in tolerance by the machine. In the case it may also reject only a sub-phase of the received jobs, putting off to the “Jobs Ready Queue” the tasks it is not able to fulfil.

The introduced semi-Heterarchical architecture represents a first attempt to face up to the NP-hard Job Shop Scheduling Problem exploiting the opportunity of an Industry 4.0 environment. However, it represents only the framework architecture without any practical algorithmic solution for the different introduced framework. In this sense, it is necessary to further investigate on this in order to establish the best heuristic or rules to be applied in every framework. The research effort must focus on the most important framework: the System of CPSs in which a cooperation algorithm is needed. In this sense, will be interesting to deepen the Cooperation Equilibrium concepts of the Game-Theory, investigating in founding a practical heuristic to solve the equilibrium problem. In the end, also in the Third Framework (inside the CPS itself), a prognostic algorithm is needed in order to estimate the current and future state of the machine.

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