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Role of simulation in industrial engineering: focus on manufacturing systems

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Abstract: Simulation has recently grown its importance thanks to the Industry 4.0, based on CPS (Cyber-Physical Systems). Especially, simulation is becoming more central for improved decision-making.
The article provides a literature analysis of peer-reviewed surveys about simulation applications in industrial engineering in manufacturing. In particular, a three-axis framework, called 3D-SAM, is proposed to classify the applications and to critically analyse them. The framework can be used as a first input for the Cognition Level of CPS (5C architecture for CPS development) in order to develop integrated simulation models within a Decision Support System (DSS).

Keywords: simulation, review, simulation application, manufacturing, DSS.

1. INTRODUCTION

In the Digitalization era, simulation covers a primary role in every field (finance, management, and manufacturing) and at all levels (strategic, tactical, and operational). In particular, the industrial engineering field, to which manufacturing belongs to, is a very flourished land for simulation development, taking advantage of the recent deployment of Cyber-Physical Systems (CPS) (Negri, Fumagalli and Macchi, 2017).

The importance of simulation in industrial engineering was already highlighted by the first pioneers in simulation research studies, since the 80s: it was considered among the first top three methodologies used by industrial engineers, managers and operations researchers (Banks, 1998). Moreover, simulation is ranked as the second most used methodologies for the OM (Operations Management) field of studies (Shafer and Smunt, 2004), only after optimisation.

This view of simulation as central in company and research is demonstrated by many research papers and empirical studies, whose number has been continuously increased since the first conceptualisation of possible uses of simulation in IE, in the mid of 80s. To figure out the amount of works done, some numbers are here provided: from 2002 to 2013, the searching process with the keywords “simulation” plus “manufacturing” finds out about 3000 published papers, whereas the overall research process with other keywords, such as “industrial engineering” or “operations”, results in around 12000 published papers in the same periods (Negahban and Smith, 2014). This results are impressive and are confirmed by another survey made in the same year (Mourtzis, Doukas and Bernidaki, 2014), for which the final detailed graph is reported.

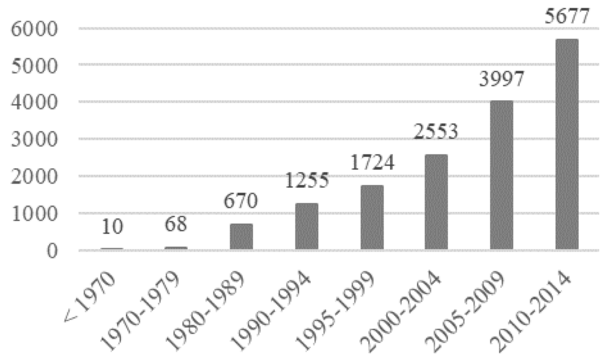

Figure 1. Numbers of publications related to simulation (Mourtzis, Doukas and Bernidaki, 2014).

Many definitions of simulation consider computer involvement as a consistent part of the definition itself: “Simulation modelling and analysis is the process of creating and experimenting with a computerised mathematical model of a physical system” (Chung, 2004). However, this definition is narrowed because it limits the application of simulation with a computerised system: the success of simulation is strictly related to computers advent (Smith, 2003), but the concept of simulation exists independently.

A simple but meaningful definition is provided by (Maria, 1997): “Simulation is a way of evaluating a proposed system for various parameters within a specific period of time”. A complete definition, and maybe the most notable, is: “Simulation is the imitation of the operation of the real-world process or system over time” (Banks, 1998). The importance of these two statements is confirmed by the continuous recalling of them into recently published papers, and so they are taken as a reference to analyse simulation-related articles in this work.

The importance of simulation in IE is evident, but which are the main applications within this field? The next sections try to answer this question, making a preliminary review of the most cited surveys in the field of IE: section 2 deals with the literature analysis of published survey/reviews, which shows up two important trends in the use of simulation; section 3 presents an elaboration of the literature review, concerning a distinction between applications used in different lifecycle phases of the industrial systems and a classification of the applications according to a three dimensional framework called 3D-SAM (3 Dimensional – Simulation Applications Model); section 4 states some conclusions about integrated simulation model for DSS (Decision Support System) in CPS; finally future works and improvements are described in section 5.

2. LITERATURE ANALYSIS

The second half of the 20th century is characterized by simulation, either in research studies either in industrial fields. The usefulness of this methodology is well-recognised, since it helps in most of the lifecycle phases of product/process/asset, thus providing important support in the decision-making process. Industrial engineers may decide for the selection of a cellular configuration for the production system instead of a transfer line layout, and asset managers could optimise the maintenance policies of a system based on simulated scenarios.
However, simulation use has evolved during these last years. The present work is confined to the analysis of “mega-trends” (high-level trends in the evolution of simulation, in the following, called simply “trend/s”) in simulation applications in the manufacturing field.
To tackle this goal, aiming at not increase variability in definitions and applications, but to use well-established concepts and analysis to create a big picture of simulation in IE, the literature review is performed as follow:

- Databases: Scopus and WoS (Web of Science) (Google Scholar is neglected due to the focus on peer-reviewed literature only, thus avoiding looking for grey literature here extensively present);
- “Search by keywords” approach: *Simulation* AND *(review* OR *literature review* OR *survey*);
- Limited to English peer-reviewed papers concerning application in manufacturing field (screened through abstract reading).

Therefore, the analysis of the literature has led to the individuation of two main trends in the use of simulation in IE. The first trend is determined by the shift from the view of manufacturing design simulation only to a wider perspective of simulation as useful during the lifecycle, for the operations management (Smith, 2003); the second trend is the increase in the number of application fields of simulation in IE (Negahban and Smith, 2014).
In the next, these two trends are analysed in the details, highlighting for each the most significant research studies.

2.1 Design to Operations trend

The first simulation application in IE regards mainly the improvement in the design phase (BOL – Beginning-Of-Life) of the system: the possibility to simulate the system before its installation has favoured all the decisions mainly regarding the layout, in terms of plant configuration, and the material movement, in terms of materials handling system. The subsequent evolution was the enlargement of the scope of simulation to the operational phase of the system, as production planning and maintenance policies (Shafer and Smunt, 2004). This increase in the use of simulation in the MOL (Middle-Of-Life) of the system has been pushed by the increase in the computing power and, mainly, by the increase in the availability of real-time shop-floor data (or close-to-real-time). This evolution could be highlighted in the next table, looking at the change in the percentage of simulation-related papers for manufacturing system design and manufacturing system operation (data adapted by (Negahban and Smith, 2014)).

Table 1. Percentages of simulation papers in function of lifecycle phases BOL and MOL.

Simulation papers		
	< 2002	***2003 < 2013***
Design (BOL)	54,45 %	26,32 %
Operations (MOL)	45,55 %	73,68 %

In spite of its importance, the EOL (End-Of-Life) of systems is not yet well analysed with a simulation perspective: decommissioning is seen as lifecycle phase involving costs (or savings) and, for these reasons, only for complex and safety-related systems simulation is used for addressing it. For instance, the decommissioning of nuclear plants has always taken advantages from simulation application (Kim *et al.*, 2006).
In this look, future research studies may be focused on the EOL lifecycle phase of industrial systems: this will improve the performance in designing and managing systems.

2.2 Applications increase trend

The increase in the use of simulation for OM purposes has brought together the increase in the interests towards some simulation-related topics or applications rather than others, but this is a continuously fluctuating trend (Pannirselvam *et al.*, 1999).

Nevertheless, it is possible to state that the applications are continuously evolving and what has certain name and scope before could have different name and scope after. It is therefore difficult to relate all the works done to the same nomenclature or classification: for this reason, a summary of the main simulation applications found in the reviewed papers is hereby reported (Table 2).

Table 2. Simulation applications per author/s.

Simulation application	**Reference survey/s**	**Description**
System design and facility design/layout	(Meredith *et al.*, 1989) (Pannirselvam *et al.*, 1999) (Smith, 2003) (Mourtzis, Doukas and Bernidaki, 2014) (Negahban and Smith, 2014)	This application concerns the design of the system and the layout of the facility to respect some constraints imposed by the process.
Material handling system design	(Smith, 2003) (Mourtzis, Doukas and Bernidaki, 2014) adapted (Negahban and Smith, 2014)	This application includes all the studies to optimise material movement.
Operations planning and scheduling	(Meredith *et al.*, 1989) (Pannirselvam *et al.*, 1999) (Smith, 2003) (Shafer and Smunt, 2004) (Negahban and Smith, 2014)	This application involves the optimisation and schedule of all the operations needed by the transformation process of the raw material in the short- and mid-term.
Real-time control	(Smith, 2003) (Negahban and Smith, 2014)	This application deals with controlling of the system regarding process parameters
Operating policies	(Smith, 2003) (Negahban and Smith, 2014)	This application analyses the policies in use to run the system.
Performance analysis	(Smith, 2003)	This application concerns with performance.
Supply chain design	(Terzi and Cavalieri, 2004) (Mourtzis, Doukas and Bernidaki, 2014)	This application involves the design of the supply chain regarding management strategies.
Supply chain management	(Terzi and Cavalieri, 2004) (Shafer and Smunt, 2004) (Mourtzis, Doukas and Bernidaki, 2014)	This application is the evolution of the previous one, used in the MOL lifecycle phase.
Process design	(Meredith *et al.*, 1989) (Pannirselvam *et al.*, 1999) (Shafer and Smunt, 2004) (Mourtzis, Doukas and Bernidaki, 2014)	This application deals with the design of the process of the system, which involves objectives and constraints.
Inventory management	(Shafer and Smunt, 2004)	This application considers stocks management.
Maintenance management	(Jahangirian *et al.*, 2010) (Negahban and Smith, 2014) adapted	This application is devoted to the management of maintenance and its strategies to improve production system availability.
Resource allocation	(Shafer and Smunt, 2004) adapted (Jahangirian *et al.*, 2010) adapted	This application involves the study regarding the most suitable allocation for each task.
Purchasing	(Shafer and Smunt, 2004) adapted (Jahangirian *et al.*, 2010) adapted	This application deals with the purchasing process.
Product design	(Mourtzis, Doukas and Bernidaki, 2014)	This application includes the simulation needed for the product design.
Ergonomics	(Mourtzis, Doukas and Bernidaki, 2014)	This application could be considered in a larger and wider goal of health management.
Knowledge management	(Jahangirian *et al.*, 2010) (Mourtzis, Doukas and Bernidaki, 2014)	The application regards knowledge dissemination through the organisation.

*"adapted" means that the name of the simulation application is not the same, but it could be easily connected to the already mentioned application (e.g. in (Mourtzis, 2014) "material handling system design" is called "material flow simulation", but the descriptions coincide).

In the proposed summary, not all the applications present in the cited papers are itemized: as a general rule, we consider a simulation application as something that responds to the following sentence: "The simulation is used for the application in … [activity]". For example, the virtual reality and CAD are not considered in the above table because virtual reality is not a proper activity, but it is something that empowers, for instance, maintenance management, and CAD is not an activity, but it is a tool which allowed improved design activity. In our opinion, some reviews make some confusion in this regarding, for example (Mourtzis, Doukas and Bernidaki, 2014) lists CAM and Process Simulation together, as if they cover the same role in simulation.
As a final remark, it is important to recall how operation phase in system is a fertile field for simulation application and how its use is increasing in time. It should be noticed that, among the possible numbers of applications, scheduling covers a primary role, as it is one of the main targets of simulation, arising to more than 30% of published papers (Jahangirian *et al.*, 2010).

3. ANALYSIS OF SIMULATION APPLICATIONS

The simulation applications presented in Table 2 are the most used in IE according to the reviewed surveys. During the analysis of these works, it becomes evident that some authors consider some applications, while other authors consider others. The aim of this preliminary work is trying to make order to the previously listed simulation applications in a double way: firstly, defining more accurately which of them could be applied in the BOL phase of the system and which could be instead used in MOL; then the applications are classified according to a 3 axes model, called 3D-SAM (3 Dimensions – Simulation Applications Model).

3.1 Simulation applications review

Before addressing the two goals highlighted above, it seemed to be useful a review of the simulation applications, trying to look for the general classification. This newborn classification is hereby presented in Table 3, in which some adjustment has been made, for example uncoupling "Operations planning" and "Scheduling", due to the importance of this last one, as anticipated in section 3.2.

Table 3. Simulation applications review.

Application
System design
Facility design/layout
Material handling system design
Operations planning
Scheduling
Real-time control
Operating policies
Supply chain design
Supply chain management
Process design
Inventory management
Maintenance management
Purchasing
Product design
Ergonomics
Knowledge management

The next section proposes the correlation of such simulation applications to the lifecycle phases of the system.

3.2. Lifecycle association

The association to the BOL and MOL phase is hereby presented (Table 4). This association between simulation applications and lifecycle phases is carried out by looking at the descriptions in the reviewed surveys. None of them clearly stated the use of simulation in EOL phase, thus no evidence to include this dimension: it should be highlighted that simulation is barely used in EOL phase in IE, except for high-risk application, as in nuclear plants decommissioning.

Table 4. Lifecycle of simulation applications.

Application	**Lifecycle**
System design	BOL
Facility design/layout	BOL
Material handling system design	BOL
Operations planning	MOL
Scheduling	MOL
Real-time control	MOL
Operating policies	MOL
Supply chain design	BOL
Supply chain management	MOL
Process design	BOL
Inventory management	MOL
Maintenance management	MOL
Purchasing	MOL
Product design	BOL
Ergonomics	BOL
Knowledge management	BOL/MOL

It is notable that some of the simulation applications associated with the MOL lifecycle phase could be used in EOL, too. This enlargement of scope can highly influence both the design phase and the operational phase of the system.

3.3 3D-SAM

This paper proposes a classification of simulation applications and, for this aim, a framework was developed, named 3D-SAM, according to which the simulation applications listed in Table 3 will be classified.

The presented framework consists of three axes defined as follows:

- *Internal dimension - design*: this dimension group together all of the simulation applications whose goal is to design an outcome (e.g. process design, whose aim is to design the manufacturing process to realise the product);
- *Internal dimension - management*: this dimension collects all the simulation applications involving the management of an entity (e.g. inventory management, whose goal is the management of the warehouse);
- *External dimension*: this dimension gathers simulations applications whose goals involve actors outside the company (e.g. supply chain design & management).

The scope of this classification is to understand the main process areas in the company in which existing simulation applications are acting. This framing is thought as a reference to support the development of integrated simulation models, composed of two or more integrated simulation applications, as better explained in section 3.4.

3.3.1 Internal dimension - design

The internal dimension - design describes the application of simulation techniques with the aim of designing an outcome, whose features and requirements are to meet organisation objectives.
Among the simulation applications enlisted in Table 3, the ones that fit such definitions are:

- System design
- Facility design/layout
- Material handling system design
- Process design
- Product design
- Ergonomics

3.3.2 Internal dimension - management

The internal dimension - management collects all the simulation applications whose goal is to enhance the management performance of an entity to reach the organisation objectives.
Referring to Table 3, the simulation applications that fall into this dimension are:

- Operations planning
- Scheduling
- Real-time control
- Operating policies
- Inventory management
- Maintenance management
- Knowledge management

3.3.3 External dimension

The external dimension gathers all of those simulation applications whose goals involve actors outside the company. This dimension is fulfilled, looking at Table 3, by:

- Supply chain design
- Supply chain management
- Purchasing

3.4 3D-SAM as a pioneer for improved decision-making

The proposed framework 3D-SAM was proposed and built up with the goal of being a first tentative guideline to pave the way for the development of integrated simulation models that support the decision-making process within an organisation, especially in the manufacturing field.
In particular, the 3D-SAM aims at giving a starting reference to be used for the Cognition Level of the CPS implementation (Lee, Bagheri and Kao, 2015) providing useful hints about the main three categories of organisation processes (internal design, internal management, and external) and needed simulation applications. In line with the definition of the CPS Cognition Level, considering the three dimensions of internal design processes, internal management processes, and external processes, highlights and unveil what simulation application may be useful to support an integrated simulation model for informed decision-making.
The understanding of what type of simulation is needed to correctly address a decision is vital to building a solid Decision Support System (DSS) that can rely on reliable, useful and quantitative data (Lee *et al.*, 2015).
The creation of an integrated DSS underlies a new bigger challenge manufacturing companies are now facing: the integration of an Asset Management (AM) system within their organisation to be more value-prone (El-Akruti, Dwight and Zhang, 2013), within DSS plays a central role to support asset-related decision-making.

Such a decision-making structure will foster the creation of a “simulation economy” of the organisation: each decision, at the strategic, tactical and operational level, will leverage on reliable data from shop-floor and will be assessed through the power of simulation in testing and validating new design and management solutions.

4. CONCLUSIONS

The analysis performed in this work is a preliminary elaboration of the reviews regarding simulation in IE in manufacturing made in the last years. The goal is to create a summary of simulation applications and make order in such a crowded field in terms of *when* some simulation applications could be used (lifecycle phases), and *where* they act in the company regarding impacted processes in terms of internal design, internal management, and external dimensions, thanks to the proposed 3D-SAM framework.
The main outcome of this preliminary analysis, which should be further assessed, are nevertheless interesting:

- A lack of simulation applications in EOL lifecycle phase is showed up;
- The first input to Cognition Level of the 5C architecture to build a CPS that may pave the way for the creation of a robust integrated simulation model for improved DSS;

- The long-term perspective of a "simulation economy" that would enhance every decision-making within the company.

Secondary outcomes of this work regard the integration of an AM system in production companies. The creation of a DSS is pushing towards this direction and, looking at one of the basic factors driving AM implementation, that is lifecycle orientation (Roda and Garetti, 2015), also the proposed cross-relationships between simulation applications and lifecycle phases enhances it.

5. FUTURE WORKS

Future works will focus on the assessment of this preliminary analysis in a double way:

- firstly, by enlarging the number of peer-reviewed papers actually included in this research by means of a more extensive literature analysis;
- secondly, by investigating more in details, through case studies from production companies, how different simulation applications, impacting on different organisation processes with different objectives, may be combine to develop an integrated DSS.

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