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Virtual engineering in the support of sustainable assembly systems

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Abstract

Virtual Engineering (VE) has always been a great aid in the design phase of manufacturing systems in terms of structural system description, behaviour simulation and interfacing between the different subsystems. To this end, virtual engineering capabilities have a strong potential to be employed in manufacturing system sustainability at different phases of the system life cycle beyond the design phase. In response to the sustainable manufacturing requirements (namely 6R), this paper discusses the opportunities VE provides to support sustainable manufacturing over the life cycle phases considering the latest industrial developments in manufacturing i.e. Industry 4.0 and smart manufacturing. A framework of virtual engineering tools integration with 6R is introduced, then a discussion of the expected contributions follows. To demonstrate the applicability of the previously mentioned concepts, a case study of an on-going industrial project is exemplified with its results discussion.

Keywords: Virtual engineering ; sustainable manufacturing; Industry 4.0; smart manufacturing; 6R

1. Background

In recent years, Virtual Engineering (VE) received remarkable attention as an enabling tool of competitiveness and productivity [1]. The term Virtual engineering (VE) originally relates to the Virtual Prototyping (VP) whether it is a product or a manufacturing system, and thus, the VE tools are either concerned with the system or the product. Nowadays, VE plays an important role in the construction of cyber-physical systems through the design validation of different factory engineering aspects such as the mechanical design, control design, process design and productivity [2]. In terms of the industrial facility anatomy, VE is able to address the factory level and the lower level machining activities [3] in addition to the component level [1, 4]. This flexibility expressed in the different levels of granularity combined with different design fields (mechanical, electrical and control) leads to a huge potential of improvement especially in the manufacturing system early design phase. The areas of influence from an Industry 4.0 perspective are: Services, Devices, Connectivity and Data [2]. Particularly, the contribution of data is vital as it affects the simulation models' accuracy and their development time.

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On the other hand, the importance of sustainable manufacturing (SM) is continuously increasing as a solution to the resources scarcity, the global willingness to reduce CO_2 emissions and the customers attraction to environment-friendly products. In accordance with this, all the emerging technologies should be exploited either to achieve this aim or to embed sustainability in design. The sustainability sources are the manufactured materials and the manufacturing processes as all the manufacturing actions aim to add value to the product [5]. From this perspective, and in addition to its usefulness as a tool that decreases time-to-market via less design effort, VE contribution can have another dimension that is sustainable design of both the manufacturing system and the product/service.

Cecil and Kanchanapiboon [3] defined the main characters a virtual model should have:

- Appearance characteristics: the ability to accurately represent the geometry and appearance of the target part, system or environment.
- Simulation characteristics: the ability to simulate engineering behaviour in terms of real-time responses.
- Representation criteria: to have the representation digitalised or computer readable.
- Interface criteria: the capability of interfacing Virtual Reality (VR) technology and graphics including supporting semi-immersive/immersive applications.

So far, there is no virtual engineering platform that supports SM despite the urgency of sustainability requirements in modern manufacturing. The novelty of this paper lies in its attempt to establish a Virtual Engineering-Sustainable Manufacturing (VESM) framework to restructure the future research in this context starting from the early design phase. The rest of this paper is structured as follows: Section II explores the literature review of VE contributions to SM and life cycle assessment in order to identify the research gap. Then, Section III discusses the vision of extending VE contribution to sustainability in smart manufacturing. A case study is shown in Section IV to demonstrate a part of the proposed concept implementation and Section V concludes the paper.

2. Literature review

Although VE tools cover the product and system design aspects, the concern in this paper is the manufacturing system design side with focus on the assembly systems. Also, the focus is not on the VE abundant commercial tools but on the contributions expressed in the capabilities they can offer.

2.1. VE for sustainability

Assad et al [6] proposed the use of a VE and discrete event simulation (DES) platform to predict energy related Key Performance Indicators (KPIs). In [7], a conceptual method that considers the Energy Consumption Units (ECUs) as the starting point to achieving system energy efficiency is introduced. Similarly, and considering component-based design, Ahmad et al [4] suggest a proactive energy consumption optimisation framework based on varying assembly component's motion profile and its cycle time. Shetty [8] recommends the deployment of VE at the levels of equipment monitoring and service to achieve sustainable design and manufacturing. The authors in [9] believe that VE creates the opportunity of cost saving by increasing the vertical integration between the different manufacturing levels which leads to further sustainability through transparent process design. Also at the component level, Ghani et al [10, 11] show that the VE 3D visualisation capability supports the modelling of energy consumption, which in turn helps building DES processes' model.

2.2. VE for life cycle assessment

Addressing manufacturing sustainability in general has a strong relation with its life cycle assessment. Therefore, assessing sustainability requires a thorough investigation of both the system and product's life cycles. On the system side, Konstantinov et al [12] showed the mechanism by which the VE tool VueOne can support the system life cycle once provided with a library of the system components in the design phase. In [13], manufacturing system's life cycle is assessed and supported by a set of VE capabilities. A VE and Virtual commissioning (VC) approach of decomposing the manufacturing system into components with levels of granularity that correspond to the level of the involvement in the life cycle is introduced in [14]. To improve the service and maintenance in discrete manufacturing machine systems, Moore et al [15] presented a VE framework of integrating 3D graphical simulations with machine fault detection.

On the product side, Padfield [16] expressed the rotorcraft industry need for VE especially in the product's early life cycle phases and considered virtual prototypes to be an important source of product's performance evaluation. VE in the form of parametric 3D CAD is considered as the basis of the product optimisation through iterative design and the transformation of product portfolio which eases the Product Life Management (PLM) [17]. The authors in [18] believe that VE via its digital tools supports Product Creation Process (PCP) through the reduction of physical prototypes and utilising virtual/augmented reality in various PCP phases. Lemu [19] believes that VE remarkably reduces the product life cycle cost, and thus, helps improve the manufacturer's competency and responsiveness in terms of lower price and shorter time-to-market.

Combining the product and manufacturing system perspectives, a Product-Process-Resource (PPR) model is introduced in [20] aiming at a better mapping of information between the three domains relying on the data obtained from a VE tools set. Also depending on the PPR approach, [21] recommends semantically integrating PPR requirements so that further simulations of their behaviour can be conducted by means of VE methods seeking the optimal design solutions. In [22], it is shown that VE tools help selecting the best production technologies, choosing product material, reducing required prototypes and the optimisation of the process parameters.

2.3. Gap analysis and research questions

The following points can be noticed based on the literature reviewed above:

- Many research papers approve VE as an effective design technology of both the product and the manufacturing system.
- VE is capable of supporting the product and the system life cycles. The main advantage behind using VE is effective data transfer between different vendors, different manufacturing system levels and stages.
- Sustainable Manufacturing requirements in relation with VE are neither framed nor systematically discussed.

Therefore, this paper attempts to answer the following research questions:

Q_1 What is the proposed framework that links VE with SM?
Q_2 How can VE tools contribute to sustainability?
Q_3 What are the expected limitations?

In the following, the holistic solution vision will be explained and a partial implementation of it will be illustrated.

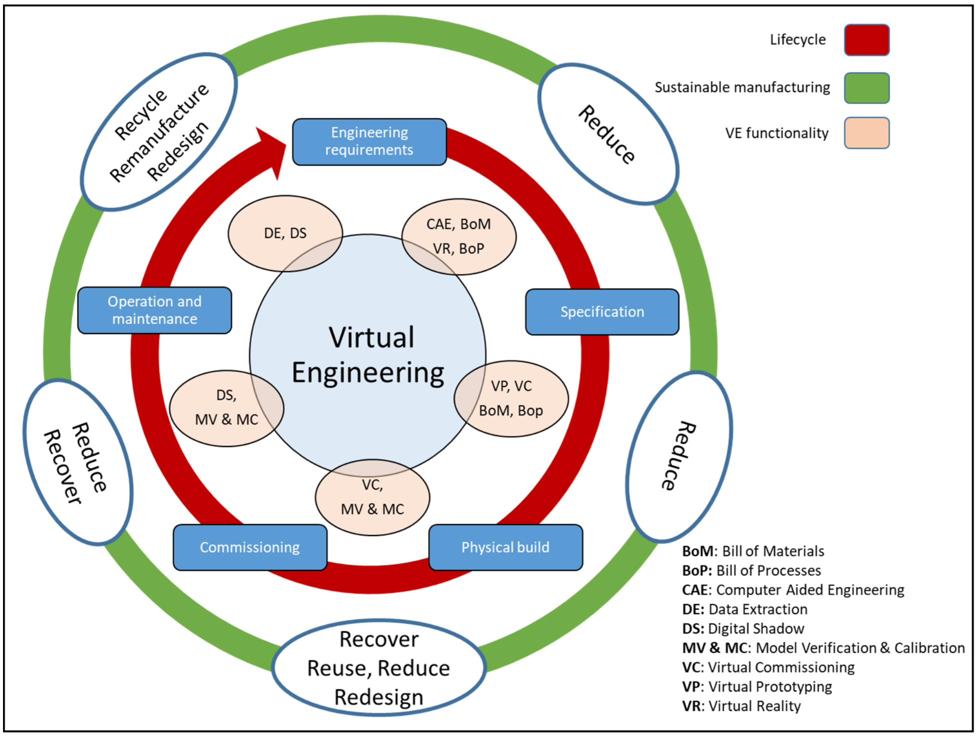

Fig. 1. A framework of virtual engineering for sustainable manufacturing (VESM)

3. Vision

In response to Q_1, a framework of integrating Sustainable Manufacturing 6R in system's life cycle using VE tools is proposed (Figure 1). Next, 6R concept, VE tools and matching 6R to VE tools are explained.

3.1. Sustainability dimensions and 6R concept

Sustainability has three dimensions: economic, social and environmental. Some metrics of sustainability are [23]:

- Environment: residues, energy use and efficiency, End-of-Life management, material use and efficiency, water use and efficiency.
- Society: education, customer satisfaction, product safety and social well-being and employee safety and health.
- Economy: cost, innovation and product quality.

For a manufacturing system to be regarded as sustainable, it should achieve 6R: Reduce, Recycle, Recover, Remanufacture, Reuse, Redesign [5]. In the following, a brief explanation of each R in the context of this paper is introduced:
Reduce: can express reducing the energy consumption or the required resources in terms of raw materials, water, time, effort, etc. Also the reduction of the system structural complexity which affects work time and required effort.
Reuse: may refer to the reuse of tools or the materials used earlier or the designs made at another phase.
Remanufacture: usually indicates the products that need repairing or minor modification to be in the accepted quality limits. Also, in this approach this action takes place after identifying the process that led to such defects.
Redesign: means redesigning the processes in terms of changing the operation parameters and the suitability of the processes/ components to the manufactured product.
Recycle: it is strongly linked to the product and similar to "Remanufacture" but the product here is no longer fixable. Therefore, it is critical to find the cause that heavily increases these particular defects.
Recover: with a direct relation to the machine's health conditions such as vibrations and energy consumption.

3.2. Manufacturing system life cycle phases

Schneider et al [13] identify the life cycle phases for cyber-physical automation systems. In this paper they are interpreted as follows:

- Engineering Requirements: The goal(s) of creating this system and the functions to be accomplished by using it.
- Specification: Deciding the stages the product will go through and the processes by which sustainable value creation takes place.
- Physical build: The physical construction of the system's units and the subsystems.
- Commissioning: Interfacing and integrating the subsystems and establishing the data communication channels.
- Operation and maintenance: Running the system and identifying the faulty components and inefficient processes.

3.3. Contribution of VE tools to sustainable manufacturing 6R

As Figure. 1 shows, there are various VE tools meant to contribute to SM depending of the life cycle phase. These tools are as follows:

Computer aided Engineering (CAE). The utilisation of CAE 3D simulation via VE environments is rapidly growing. This includes the design of components and the assembly processes in addition to the ability of interfacing Finite Element Analysis (FEA) with multi-body systems [19]. Potential VE contributions can be the lightweight design facilitation, choice of energy efficient components accompanied by Key Performance Indicators' (KPI)'s calculations [6].

Bill of Materials (BoM). BoM is essential to the parts purchase and construction planning. The materials needed for the manufacturing system's parts are estimated through BoM in order to achieve savings and possible alternatives. Additionally, BoM is indicative of the energy consumption units as it contains the components that are going to be connected to the Programmable Logical Controller (PLC) via input/output modules [7].

Bill of Processes (BoP). It expresses a repository system to store and reuse design mechanisms and manufacturing process modules that guarantees the reuse of engineering knowledge [24] in addition to the used resources (materials, energy, water, emissions and wastes) [25].

Virtual Reality (VR). The visualisation of engineered systems is an important VE characteristic [13]. Many process, product and resource (energy/material) related indicators can be visualised interactively with the proposed design scenarios.

Virtual Prototyping (VP). Providing the virtual types of the product/assembled product, components and sub-assemblies is vital when moving to the physical build phase. Thus, reducing the amount of scrap due to the variation from VP in addition to the energy consumed while operating the system. Moreover, Lemu [19] includes the ability to add friction and forces in the prototyping procedure. Consequently, the resultant losses in both material and energy can be envisaged.

Virtual Commissioning (VC). It aims at validating the system's control programme by connecting the physical/virtual controller to the virtual production system [7]. Then, the system response can be recorded and analysed to determine the suitability of the control algorithm in terms of energy consumption and induced vibration, thus, a recovery action will take place next. Therefore, VC gives the advantage of reusing the components and reconfiguring them to analyse the corresponding performance [14].

Model verification and calibration (MV & MC). It closes the gap between the virtual system and real system and involves the reuse of subsystems [2]. The model generated earlier is calibrated to recover the processes whose cycle times suffer a great variation or consume energy excessively. Similarly, the product features that cause such incidents are reported to be redesigned along with the processes. Then, if applicable, both product features and manufacturing processes are recovered and the updated parameters are transferred into the model.

Digital Shadow (DS). After the successful commissioning, the virtual "copy" of the system and the product(s) are stored in the form of a virtual model. This can be the basis of recovering the unhealthy components/process and reducing the variation in processes' parameters. For example, Holger et al [26] exemplified the use of the simulation model built using virtual engineering for process monitoring which constitutes the first step to starting predictive maintenance. It should be noted that the data transfer takes place in one direction that is from the physical model to the virtual model.

Data Extraction (DE). AutomationML™ for example is a possible choice when it comes to engineering data exchange between different partners [14]. In fact, the output data assists in decision making in terms of the amount of resultant products that need to be recycled, and thus, estimating the manufacturing system resources efficiency. Another aspect is to redesign the processes that did not give the expected outcome and the products that do not correspond to the predefined standards. Also, some products would not be partly defected so that subjecting them to remanufacturing would overcome the defects. In total, the historical records of the system performance indicators extracted from VE model play an important role in decision making in terms of remanufacturing, recycling and redesign.

4. Case study

In this section, a part of the previously proposed vision is exemplified. This includes the move form "Physical Build" phase to "Commissioning" aided by "Virtual Commissioning" and "Model Verification and Calibration" in order to achieve "Recover", "Reduce", "Redesign" and "Reuse".

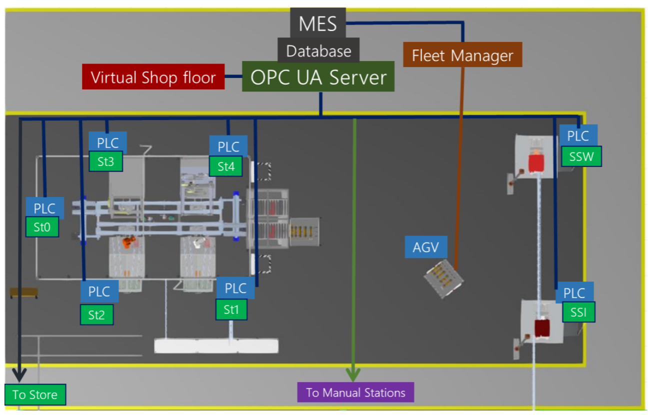

Fig. 2. WMG IML layout

4.1. Case description

Integrated Manufacturing and Logistics (IML) production demonstrator implemented in WMG - University of Warwick workshop was chosen as a case study for the paper. IML showcases Industry 4.0 methods and new production systems within a series of advanced manufacturing scenarios. Virtual Layout with the main stations are shown in Figure 2. The manufacturing system contains a number of subsystems:

- Legacy Loop subsystem: responsible for the assembly.
- Stand-alone welding station uses robotic spot welding.
- Stand-alone inspection station contains a robot with camera to conduct quality check of the product.
- Manual assembly stations and store.
- Autonomous Guided Vehicles (AGV) and conveyor.
- Control System Architecture: Manufacturing Execution System (MES), common data model (databases), OPC UA server (communication), Visual Components software application (VE tool), Discrete Event Simulation (DES) application and Fleet Manager.

4.2. Implementation and results

The stations were modelled and virtually simulated for manufacturing processes development. Some of the stations were virtually commissioned to reduce PLC code errors and prevent physical damage of the equipment during the debugging of PLC programmes on physical machines. Figure 3 shows an example of virtually commissioning the Visual Inspection station. The virtual model was connected to and driven by Rockwell PLC via OPC UA client-server communication which allowed testing the code in a virtual environment to prevent the possible errors during physical commissioning.

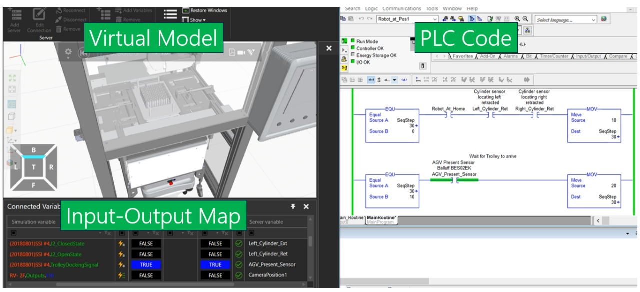

Fig. 3. Virtual commissioning of the visual inspection station

Thus, the targeted Rs of SM are achieved as follows:

- *Reuse*: The virtual components generated earlier were reused to save the commissioning time and prevent as much as possible any physical damage.
- *Recover*: The errors in the PLC codes were recovered. Also, the model verification and calibration in terms of cycle time was accomplished (processes recovery). Figure 4 shows the adjustment of the inspection process steps cycle time after detecting the variation between the physical system and the virtual model.
- *Reduce*: Further to the adjustment of cycle times, the system downtime could be reduced leading to less energy consumption. Figure 5 shows graphically the amount of reduced energy consumption in each station individually and the total one. Numerically, the amounts of reduction are: Station1 5.3%, Station2 3.8%, Station3 4.67%, Station4 2.33%, all stations 4.1%.
- *Redesign*: This improvement is attributed to the "redesign" of the process's logic (PLC code).

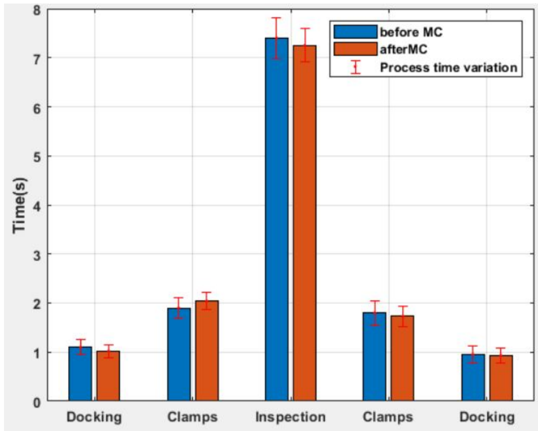

Fig. 4. Cycle times of inspection process steps after MC & MV

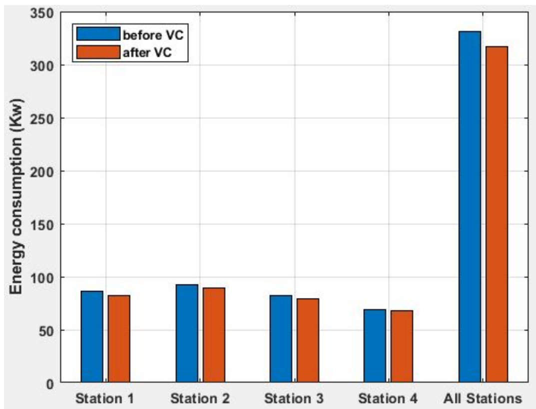

Fig. 5. Energy consumption reduction in each station after VC

4.3. Limitations and challenges

Despite many achievements in sustainability, VE as a business model is not studied in this research. There are many indications in literature to the capabilities provided by Industry 4.0 to the Small and Medium Enterprises (SMEs). However, they are not discussed here.

On the technical side, a complete virtual system on one layout is "heavy" in terms of high computing power to handle the 3D graphics and processes. The full virtual plant model requires further development of the connectivity with different

PLCs and MES system so that any changes at the physical level are updated in the database and the virtual plant model. The virtual model should also provide the ability of extracting different types of data, e.g. maintenance documents, operator instructions, BoM and BoP. This data shall be automatically generated in a suitable format and further integrated to the Digital Twin scope.

In general, VC requires additional effort of developing virtual models, simulations and connectivity with IO (Input-Output) mapping to a PLC. This can extend the project time and costs.

5. Conclusion and outlook

In light of the recent changes in manufacturing and the increased tendency to virtualisation in addition to the sustainability requirements, this paper attempted to shed light on VE's possible contributions to sustainability. A framework based on sustainable manufacturing 6R requirements is structured in order to enhance sustainability over different phases of the manufacturing system life cycle. The contributions of each suggested use of the digital tools are shown depending on the life cycle phase. In addition, the expected limitations and challenges are shown. The introduced framework can cover both the product and manufacturing system life cycles. As a result, sustainability has the potential to be enhanced in the economic, environmental and social dimensions although they are not all covered currently but in planned future work.

On the technical level, further work is required to accomplish VCs and create digital twins/shadows of all the stations. The final aim is to merge the physical and virtual systems in a single consistent environment towards Digital Factory framework. DS is intended to provide automatic virtual model verification and calibration according to physical model processes' parameters (e.g. speed, time).

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