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The HORSE Project: The Application of Business Process Management for Flexibility in Smart Manufacturing

Jonnro Erasmus [1], Irene Vanderfeesten [1,2,*], Konstantinos Traganos [1], Ruud Keulen [3] and Paul Grefen [1]

1 Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands; j.erasmus@tue.nl (J.E.); k.traganos@tue.nl (K.T.); p.w.p.j.grefen@tue.nl (P.G.)
2 Department of Information Sciences, Open University of the Netherlands, PO Box 2960, 6401 DL Heerlen, The Netherlands
3 Thomas Regout International B.V., Maastricht Industrieweg 40, 6219 NR Maastricht, The Netherlands; r.keulen@thomasregout.com
* Correspondence: i.t.p.vanderfeesten@tue.nl

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Abstract: Several high-tech manufacturing technologies are emerging to meet the demand for mass customized products. These technologies include configurable robots, augmented reality and the Internet-of-Things. Manufacturing enterprises can leverage these new technologies to pursue increased flexibility, i.e., the ability to perform a larger variety of activities within a shorter time. However, the flexibility offered by these new technologies is not fully exploited, because current operations management techniques are not dynamic enough to support high variability and frequent change. The HORSE Project investigated several of the new technologies to find novel ways to improve flexibility, as part of the Horizon 2020 research and innovation program. The purpose of the project was to develop a system, integrating these new technologies, to support efficient and flexible manufacturing. This article presents the core result of the project: a reference architecture for a manufacturing operations management system. It is based on the application and extension of business process management (BPM) to manage dynamic manufacturing processes. It is argued that BPM can complement current operations management techniques by acting as an orchestrator in manufacturing processes augmented by smart technologies. Building on well-known information systems' architecting frameworks, design science research is performed to determine how BPM can be applied and adapted in smart manufacturing operations. The resulting reference architecture is realized in a concrete HORSE system and deployed and evaluated in ten practical cases, of which one is discussed in detail. It is shown that the developed system can flexibly orchestrate the manufacturing process through vertical control of all agents, and dynamic allocation of agents in the manufacturing process. Based on that, we conclude that BPM can be applied to overcome some of the obstacles toward increased flexibility and smart manufacturing.

Keywords: business process management; manufacturing operations; flexibility; horizontal and vertical integration; smart factory; industry 4.0; industrial internet-of-things

1. Introduction

Manufacturing enterprises have sought process improvement since the dawn of the industrial age. Production lines and division of labour brought early gains in productivity. Automation further increased productivity, especially when paired with computer control systems. Such process improvements are enabled by technological advancement in response to demand. Figure 1 illustrates the forces of technological push and requirements pull as the drivers of improvement.

Figure 1. Interacting forces towards flexibility (adapted from [1]).

Responding to both push and pull mechanisms, various types of manufacturing systems have been created. Dedicated manufacturing systems led to the rise of mass-produced and more affordable products [2,3]. Flexible manufacturing systems responded to the need for factories to produce a large variety of products at small scales. These systems represented two extremes: (1) dedicated manufacturing systems with low flexibility and low cost per product, and (2) flexible manufacturing systems with high flexibility and high cost per product.

Eventually, the need arose for dedicated manufacturing systems to be more flexible, to be able to respond to fluctuations in market demand and the availability of materials and resources [4]. The response was a reconfigurable manufacturing system, named in reference to the use of configurable tools to achieve small production runs and reasonably quick change-over [5]. Moreover, the manufacturing system is designed around the part family, with the customized flexibility required for producing all parts of this part family [6]. However, the desire for personal and individual products is leading to a rapid increase in the demand for mass customisable products. This is more evident in high-tech products of high value, such as automobiles and aircraft, but the phenomenon is even spreading to traditional products [7]. Increased product customisation and variation places new demands on manufacturing systems. The following effects can be identified [8]:

- Batch sizes are shrinking to accommodate more product variation, leading to frequent production downtime for system reconfiguration and tool change-over;
- More product variation necessitates more versatile production operations, as a larger variety of material and product transformations are needed;
- A wider range of product specifications and more production possibilities introduce significantly more complexity into the planning and operations management;
- More complexity leads to uncertainty, because the manufacturing processes and resources have a more unpredictable impact on the product.

Manufacturing systems must become more flexible to produce more varied products [9]. The extent of the variation is also increasing, with customers exploring the possibilities of truly personalised products [10]. Such variability necessitates ever greater process flexibility and versatile production resources [11–13]. By positioning manufacturing flexibility as the improvement in Figure 1, we see that demand fluctuation and mass customisation pulls manufacturers towards volume and product flexibility. Meanwhile, new technologies push factories towards technology and equipment flexibility.

Market pull and technological push are increasing uncertainty and the demand for manufacturing flexibility. Sawhney [14] assimilates the two concepts of uncertainty and flexibility into a framework. The argument is made that flexibility is a coping mechanism against the uncertainty inherent to any manufacturing enterprise. Uncertainty is present at every stage of an enterprise and flexibility can help to lessen the effect of uncertainty. More importantly, the overall flexibility of an enterprise is a function of the flexibility at its input, process and output stages. Input flexibility is affected by the flexibility of suppliers and, thus uncertainty can be reduced with surplus inventory or strategic partnerships. Output flexibility is necessary to deal with the uncertainty of demand and customer expectations.

Process flexibility is determined by its components, including the flexibility of human resources, equipment and operations. By extension, increased process flexibility is an attempt to minimise the impact of uncertainties associated with process components. For example, the uncertainty of machine reliability can be mitigated with the flexibility afforded by multiple machines or the ability to reroute operations to a different machine.

Manufacturing flexibility can be divided between internal and external flexibility [15]. External flexibility takes a broad perspective, focused on the supply chain (supplier flexibility) and time to market (customer flexibility). In contrast, internal flexibility refers to the ability of a firm to economically and effectively change operations, with a focus on the flexibility of alternative process configurations and technologies. In Figure 2 our view on manufacturing flexibility is presented, inspired by the frameworks of [14,15]. Internal flexibility is shown inside the manufacturer box, composed of input, process and output flexibility.

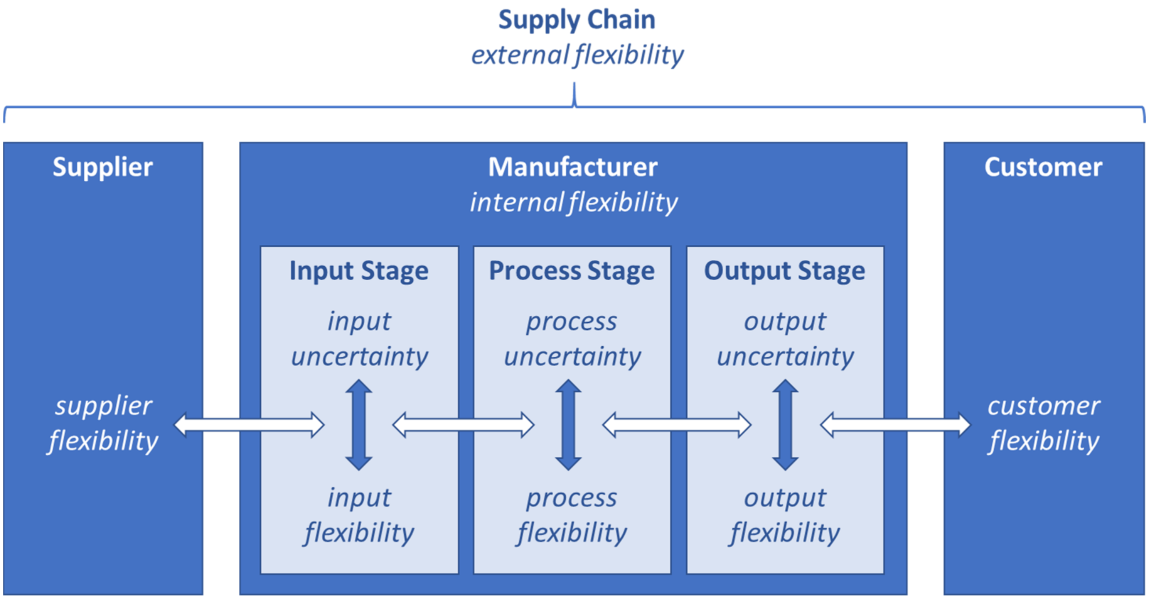

Figure 2. Framework depicting various types of flexibility in manufacturing, inspired by [14,15].

1.1. Problem Statement

The research presented in this manuscript is primarily interested in the *internal flexibility* of an enterprise, more specifically, in *process-related issues* that inhibit the flexibility needed for Industry 4.0. By focusing on the process stage in the Sawhney framework [14], through literature review and exploratory case study observations, we identified process-related issues on the following three levels:

1. Poor interoperability of the input, process and output stages of a manufacturing system limits the capacity to respond to demand and supply uncertainties;
2. Insufficient process flexibility decreases the ability to adapt to changes in the manufacturing system caused by internal or external uncertainties;
3. Inflexible utilisation of resources (humans, equipment, tools, etc.) limits the versatility needed to produce varied products.

Interoperability has a significant impact on flexibility [16]. Internal flexibility is affected by the interoperability of the input, process and output stages of the manufacturing system. Stated differently, flexibility is affected by the broad manufacturing process, stretching across multiple business functions, including supply chain management, operations, product delivery and after-sales support. Consequently, cross-functional process integration is a crucial step towards smart manufacturing, but remains a problem with no clear solution [17–19].

Cross-functional process integration helps a manufacturing system respond to fluctuating demand and supply factors, but it does not address the higher product-mix demanded in Industry 4.0. Product flexibility is dependent on production flexibility. As such, the process itself must be sufficiently flexible to achieve the expected product-mix flexibility. However, current manufacturing process management techniques are notoriously rigid [20,21]. In fact, the rigidity of traditional graphical process models has been considered as the main source of process inflexibility [22,23]. Furthermore, the information systems that manage process execution are often blamed for process inflexibility [24,25].

Lastly, the people and machines that participate in the processes must be able to adapt to the changes caused by demand fluctuation, product customisation and dynamic reconfiguration. In fact, the increased versatility offered by smart devices and mobile technology is expected to be a key enabler for Industry 4.0 [26–28]. However, the control systems of machines and robots are not well suited to frequent changes in the environment and production specifications [29]. Such control systems are typically dedicated to a specific set of activities in a predefined area of a factory. Allowing operators and equipment to cross functional barriers goes beyond the capabilities of current control systems. These systems also tend to be proprietary, resulting in fragmented resource control in a technologically heterogeneous factory [30]. Thus, a factory seeks the ability to dynamically alter the configuration of human operators, machines and activities, but cannot effect such changes from a central point of control.

In summary, the following process-related problems emerge in smart manufacturing, all contributing to an inability to increase the internal flexibility of an enterprise:

- Process management in manufacturing is fragmented, with different techniques applied to different parts of the enterprise;
- Smart technologies, such as versatile robots and autonomous guided vehicles, are under-utilized, because the rigid process design and management does not encourage rapid reconfiguration and reassignment of resources;
- The number of hardware and software systems continue to increase, based on different control regimes from different vendors. These systems are difficult to integrate and utilise together in the same process.

These three emerging problems can be distilled into a single problem statement, by focusing on manufacturing process management as the common factor. Therefore, the following problem statement is used as the central motivation in this research: *Current manufacturing process management techniques and technologies are not well equipped for the flexibility needed in Industry 4.0.*

1.2. Research Context

This research is motivated by the problems encountered in a smart factory. A smart factory can be defined as "the integration of all recent IoT technological advances in computer networks, data integration, and analytics to bring transparency to all manufacturing factories" [31]. NIST defines a smart factory as a "fully integrated, collaborative manufacturing system that respond in real time to meet changing demands and conditions in the factory, in the supply network and in customer needs" [32]. By juxtaposing a smart factory to a traditional manufacturing system, six differences are enumerated in Table 1 [33].

Table 1. Comparison of the smart and traditional factory [33].

Nr	Traditional Manufacturing System	Smart Manufacturing System
1	Limited and Predetermined Resources. To build a fixed line for mass production of a special product type, the needed resources are carefully calculated, tailored, and configured to minimize resource redundancy.	Diverse Resources. To produce multiple types of small-lot products, more resources of different types should be able to coexist in the system.
2	Fixed Routing. The production line is fixed unless manually reconfigured by people with system power down.	Dynamic Routing. When switching between different types of products, the needed resources and the route to link these resources should be reconfigured automatically and on-line.
3	Shop Floor Control Network. The field buses may be used to connect the controller with its slave stations. But communication among machines is not necessary.	Comprehensive Connections. The machines, products, information systems, and people are connected and interact with each other through the high-speed network infrastructure.
4	Separated Layer. The field devices are separated from the upper information systems.	Deep Convergence. The smart factory operates in a networked environment where the wireless network and the cloud integrate all the physical artefacts and information systems to form the IoT and services.
5	Independent Control. Every machine is pre-programmed to perform the assigned functions. Any malfunction of single device will break the full line.	Self-Organization. The control function distributes to multiple entities. These smart entities negotiate with each other to organize themselves to cope with system dynamics.
6	Isolated Information. The machine may record its own process information. But this information is seldom used by others.	Big Data. The smart artefacts can produce massive data, the high bandwidth network can transfer them, and the cloud can process the big data.

Kang et al. [34] are more interested in the integrative nature of a smart factory. The following three features are offered to recognise the realisation of a smart factory: (1) horizontal integration of value networks, (2) vertical integration of manufacturing systems, and (3) end-to-end digital integration. Horizontal integration occurs between enterprises, to achieve integration of resources, systems and processes. Vertical integration focuses on integration of manufacturing systems within the factory production [35]. The end-to-end digital integration is a result of the horizontal and vertical integration, to achieve product customization [36].

Regardless of the precise features and components of a smart factory, the goal is ultimately to increase intelligence, flexibility and cost-effectiveness [36,37]. The integration of machines products and resources should improve the self-optimization of the production process and meet customer requirements by enabling mass customization [36,37].

For the purposes of this research, a smart factory is defined as a manufacturing system utilising at least one of the following technologies:

- Actors (both human and automated) that are connected to the factory control systems, adaptable and able to collaborate to perform manufacturing tasks;
- Manufacturing processes that can dynamically reconfigure for each instance of a product;
- Object recognition technology to assist human and automated actors to identify, manipulate or modify highly variable products.

1.3. Proposition

We hypothesize that business process management (BPM) can be applied for manufacturing processes, to alleviate the problems encountered in smart manufacturing. BPM is a discipline in operations management in which people use various methods to discover, model, analyse, measure, improve, optimize, and automate (end-to-end) business processes [38,39].

Although BPM was born out of the principles of production engineering, it has been most successful in industry sectors that process information, rather than physical material. Most prominently, BPM has been implemented extensively and successfully in financial service organisations [40,41]. Nevertheless, several other industry sectors have also seen benefits from the application of BPM, including sectors with a 'physical nature' like automotive [42] and transportation [43]. However, these applications of BPM almost exclusively focus on the business management functions in those industry sectors, rather than the activities that 'touch' the product. A surprising outlier is the healthcare sector, where patient handling processes are modelled and sometimes enacted using a business process management system (BPMS) [44–48]. The advent of the Internet-of-Things (IoT) has sparked the combination of physical objects and business process management [49], but most of this work is in a rather early stage, without adequate attention to structured approaches for modelling complex applications.

The potential benefits of BPM in manufacturing has been considered though, especially with the rise of smart technologies [50,51]. Indeed, BPM holds distinct advantages of interest in this research, especially for small and medium enterprises. Table 2 shows how BPM may help to alleviate the problems identified in Section 1.

Table 2. Indication of how business process management (BPM) may help to alleviate some of the problems identified in smart manufacturing.

Problem	Solution
Process management in manufacturing is fragmented, with different techniques applied to different parts of the enterprise.	BPM is often deployed to improve enterprise integration [52].
Smart technologies are under-utilized, because the rigid process design and management does not encourage rapid reconfiguration and reassignment of resources.	BPM is often used for dynamic processes [53,54].
The number of hardware and software systems continue to increase, based on different control regimes from different vendors. These systems are difficult to integrate and utilise together in the same process.	BPM can orchestrate the activities of different resources, because it is technology agnostic [55].

The solutions listed in Table 2 often rely on a business process management system (BPMS). Such an information system can be used to manage hundreds of unique process instances across multiple business units and can assign work items to specific resources, based on the logic encoded into the process models. Furthermore, a BPMS can utilise general-purpose technology integration approaches (e.g., middleware) to interact with a variety of enterprise information systems. These information systems are versatile and mature, prompting the proposal that they might benefit manufacturing.

Firstly, this article presents the HORSE System, a reference architecture for a manufacturing operations management system (MOMS). At the core of this system architecture is a BPMS supplemented with several other cyber physical systems and technologies, including a sophisticated multi-actor control system and augmented reality functionality. Secondly, the reference architecture is also realised as a prototype and presented as demonstration in this article, giving evidence that the developed system indeed helps to overcome some of the obstacles toward increased flexibility and smart manufacturing. The prototype systems are deployed and verified in real production environments, placing the HORSE System at technology readiness level 6 [56,57].

To be clear, this research proposes the addition of BPMton manufacturing, rather than replacing current techniques and technologies. Manufacturing processes are typically performed according to a strict schedule and in adherence to policies and procedures. BPM techniques and technologies can be used to define and enact the manufacturing processes, in accordance to the schedule, policies and procedures. Thus, the BPMS supports execution of the manufacturing operations as planned in the schedule.

2. Materials and Methods

The research presented in this article is the result of the HORSE Project (www.horse-project.eu), a multi-year research and innovation project funded by the European Commission under the Horizon 2020 program. The project aims to make advanced manufacturing technology more accessible to small and medium enterprises, improving their flexibility and competitiveness [58]. These technologies, including collaborative robotics, teaching-by-demonstration and augmented reality, are developed and integrated in a reference architecture of a modern manufacturing operations management system, named the HORSE System.

The project consortium includes 21 organisations across Europe, including universities, research institutions and commercial enterprises. Thirteen of the 21 organisations are commercial factories located across Europe. These factories will serve two purposes related to this research: (1) Serve as inspiration for the problems encountered when introducing smart manufacturing technology, and (2) Serve as appropriate environments to implement and evaluate instantiations of the HORSE System.

2.1. Research Objective

Applying BPM in manufacturing has seen some attention. Its integrative potential has not gone unnoticed by researchers in the manufacturing domain. Prades et al. [59] make the case for integration between enterprise resource planning (on level 4 of the functional hierarchy defined in the IEC 62264 standard) and manufacturing operations management (on level 3), by using Business Process Model & Notation (BPMN) for process modelling in both levels. Gerber et al. [60] also pursue integration, but instead opt for translation from level 4 BPMN models to level 3 sequential function charts. Comparatively, subject-oriented business process management (S-BPM) has been demonstrated as an enabler of integration in smart manufacturing [61–63].

This research compliments and builds on those previous efforts, but aims for a more comprehensive theory on the application of BPM in smart manufacturing operations. This work is more comprehensive because it adds the following elements that remain unaddressed until now:

1. The development of a reference architecture of an integrated and modular information system to manage smart manufacturing processes;
2. The inclusion of several emerging technologies, such as collaborative robotics, augmented reality and teaching-by-demonstration, to enable smart manufacturing;
3. The inclusion of functionality that enhances process flexibility by enables dynamic routing and selection of operators or machines to perform tasks;
4. The theory and technology are applied to and evaluated with real cases in the manufacturing domain.

This research proposes the use of BPM in manufacturing operations management. However, manufacturing operations management is undergoing disruption with the advent of smart technologies. As such, the existing knowledge of BPM is applied to the new problems encountered in manufacturing. Gregor and Hevner [64] refer to this type of research as *exaptation*, as a subset of design science research. Exaptation is a term borrowed from evolutionary biology, referring to the repurposing of existing traits for new problems. It is defined by Gregor and Hevner as “extend known solutions to new problems (e.g., adopt solutions from other fields)”. This research goes beyond pure exaptation though and enters the domain of *improvement*, defined by Gregor and Hevner as “develop new solutions to known problems”. BPM is not only applied in smart manufacturing, but it is also adapted to be more suitable. Specifically, functionality is added to provide the dynamic allocation of manufacturing tasks to actors, as discussed in Section 3.2. This improvement supports the goal of increased manufacturing flexibility, because it allows readjustment of the process and process participants during run-time, based on the latest information from the factory floor.

2.2. Research Design

To recap, the objective of this research is the following: To develop a theory for the exaptation of business process management in smart manufacturing operations to increase flexibility. The information systems research framework of Hevner et al. [65] is used to frame and position the core concepts of this research. This framework advocates for due consideration of the business needs from the environment (guarding the relevance of the research) and applicable knowledge from the scientific knowledge base (guarding the rigor of the research). The environment and knowledge base also serve as avenues for the output of the research. Developments should be applied in an appropriate environment and generated knowledge should be added to the knowledge base. As illustrated in Figure 3, the environment, research and knowledge base lanes of the Hevner et al. [65] design science research framework are used to structure the ingredients, activities and core research concepts advocated by Verschuren and Doorewaard [66]. The environment provides the business needs to be addressed and an appropriate environment for evaluation of the HORSE system. The research lane depicts the two major activities to be performed: development of the HORSE system and evaluation through verification and validation. Lastly, the knowledge base provides established the scientific literature and methodologies on (problems) in smart manufacturing and best practices in information systems development and software engineering.

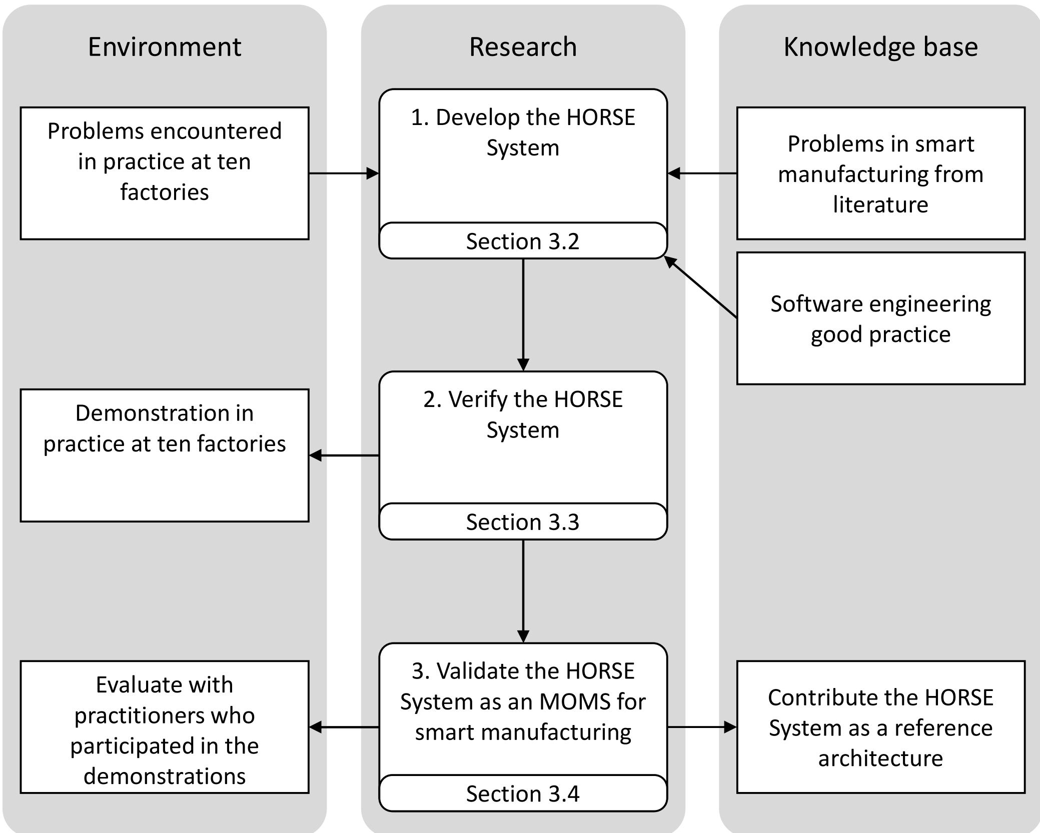

Figure 3. Research framework for this research, based on the framework of Hevner et al. [65].

The ten factories serve as the inspiration and as a representative set of problems that are encountered in smart manufacturing. Those problems are complemented by problems discussed in the literature. Only a concise overview of the problems is discussed in Section 1 of this article, in the interest of brevity. The HORSE System is developed to alleviate the problems and then demonstrated as such in the same ten factories. To gauge the experience of the practitioners who interacted with the system, the usefulness and ease-of-use is measured, based on the Technology Acceptance Model [67]. The validated system architecture is thus positioned as a reference architecture for a manufacturing operations management system for smart manufacturing and, as such, a contribution to the knowledge base.

3. Results

This research proposes the HORSE System as a demonstration for the exaptation of BPM to manufacturing and the HORSE System architecture as a reference architecture for a smart manufacturing operations management system. This section constitutes the main argument and is presented in four parts: (1) an explanation and justification for the role of the HORSE System in the context of manufacturing operations management, (2) the design of the HORSE System, showing cross-functional process management and control of individual actors, (3) a demonstration of the HORSE System prototype in practice, and (4) an evaluation based on the acceptability of this new technology for the practitioners.

3.1. Unified Process Management in Smart Manufacturing

In earlier work [68], we argued that a BPMS can be used as a central orchestration hub for humans, robots and other actors. The argument is predicated on the fragmented state of manufacturing operations management. Different information systems are typically used to manage the business and operation activities, causing process throughput deficiencies. In fact, improved integration is considered a crucial step towards smart manufacturing [17–19].

The IEC62264 series of international standards is a long-running development dedicated to the pursuit of integration in manufacturing enterprises [69]. The first part in the series provides a hierarchy of functional control, as illustrated in Figure 4. The hierarchy is a framework to classify control functions according to their purpose [70]. For example, production scheduling is a level 4 function, while dispatching resources according to the schedule is a level 3 function.

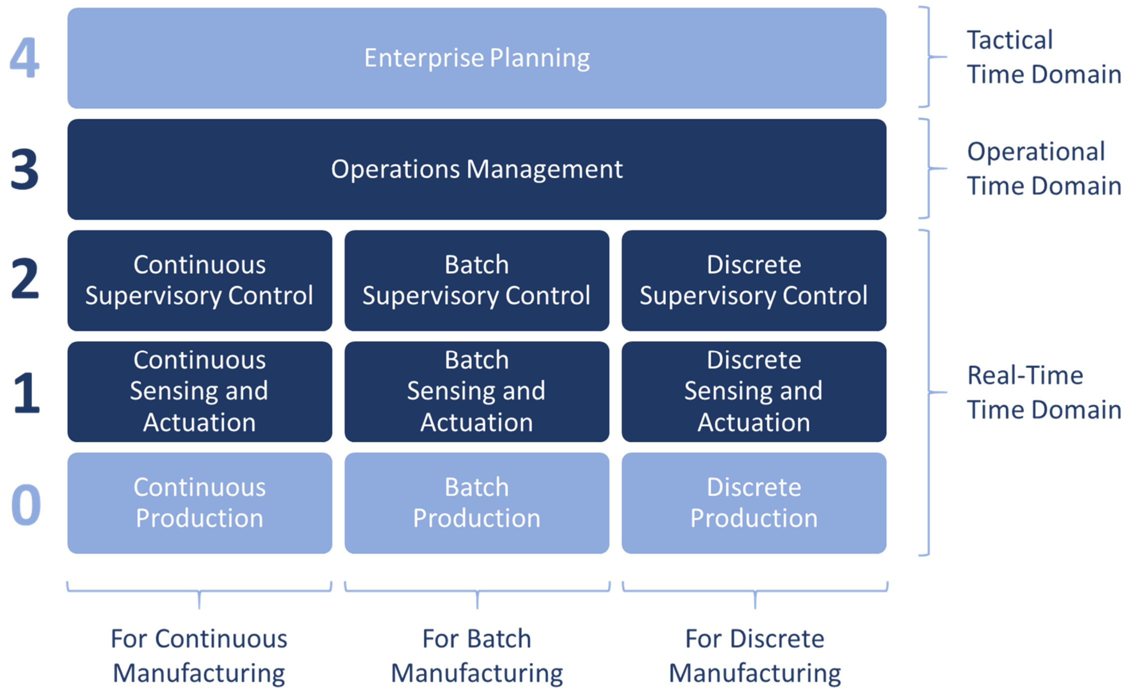

Figure 4. Hierarchy of functional control, inspired by IEC62264:2013 [70].

We propose that a single system, in this case the HORSE System, can serve as a single workflow management system across all manufacturing operations (on level 3 of Figure 4). The BPMS at its core delivers seamless integration with level 4 (see Figure 4), as such systems are widely adopted for level 4 enterprise information systems.

Figure 5 shows the run-time subsystems of the HORSE System in the enterprise architecture of computer integrated manufacturing. As a central orchestrating hub, the HORSE System drives integration in two ways: (1) cross-functional process management on level 3 (horizontal integration across manufacturing operations), and (2) the coordination of actors on level 1 of the functional control hierarchy (vertical integration across hierarchy levels).

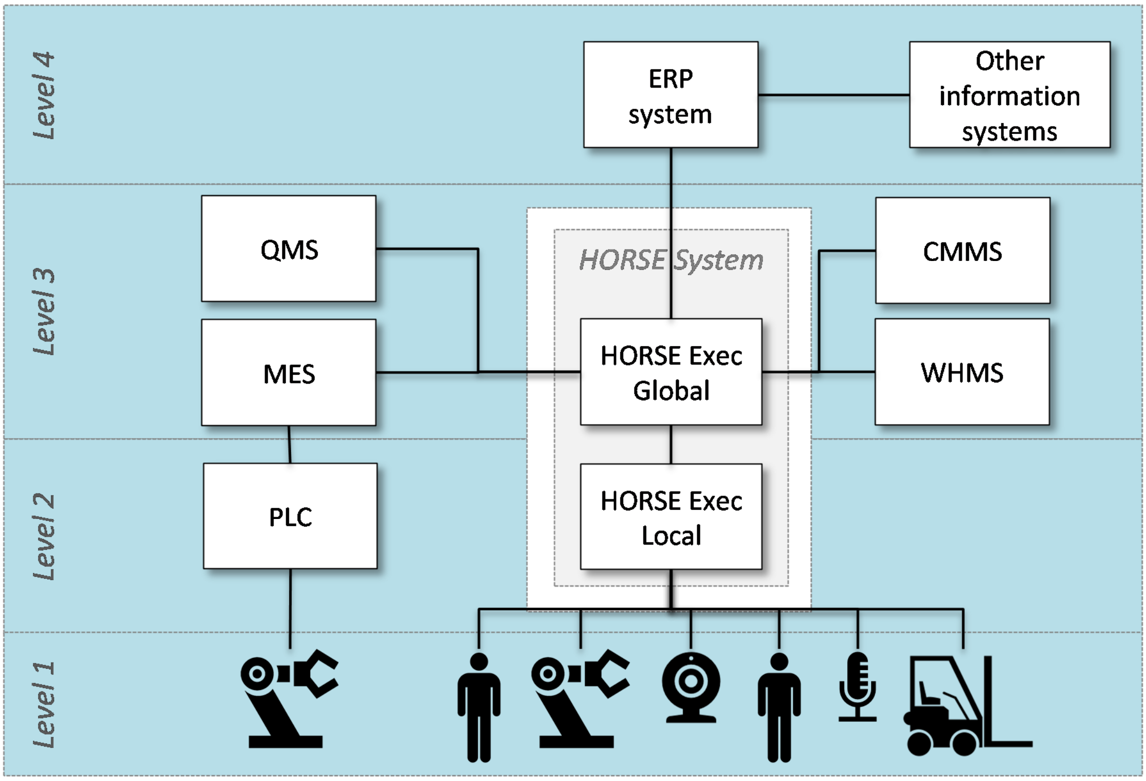

Figure 5. The HORSE System positioned in the functional hierarchy of IEC62264:2013-1. The symbols in level 1 represent a variety of "things" in the IoT paradigm. From left to right, the symbols represent a robot, a human, another robot, a video sensor, another human, an audio sensor and an autonomous vehicle.

Correspondingly, the HORSE System is divided into two components, named HORSE Exec Global and HORSE Exec Local. Thus, the system architecture complies to the levels of the IEC62264:2013-1 functional hierarchy and caters for the different types of control used at levels 2 and 3. The HORSE Exec Global subsystem provides workflow control across several work cells occupied by multiple actors. The HORSE Exec Local subsystem provides control of individual actors or teams of actors. As such, the HORSE Exec Local subsystem is a realization of the internet-of-things, acting as the connection between the process management system and the devices. This realization is discussed in detail by Grefen et al. [71]. Separate interfaces between manufacturing operations management systems and other control systems are still possible, as shown by the interface between the MES and PLC in Figure 5.

3.2. The HORSE System Architecture

The HORSE Project aims to bring together, develop and refine advanced manufacturing technology in a package that is accessible to SMEs. The technologies include human–robot collaboration, situational awareness, robot teaching-by-demonstration and augmented reality. The various technologies are packaged in modular and integrated information system architecture, appropriately named the HORSE System, such that an SME can easily deploy selected technologies at its premises.

The design of the HORSE System is extensively elaborated in previous articles [58,72,73]. Several videos of the HORSE System and its various technologies can also be found on the HORSE Project website (http://www.horse-project.eu/Media). The video labelled 'MPMS demo video' gives an overview of the use of the business process management in the HORSE System.

As a brief overview of the HORSE System, it has a layered architecture pattern, with a global orchestration layer and a local control layer [74]. Figure 6 shows a model of the HORSE System. The upper layer represents global control and the lower layer contains the technologies that are utilized by a human or robot on the factory floor.

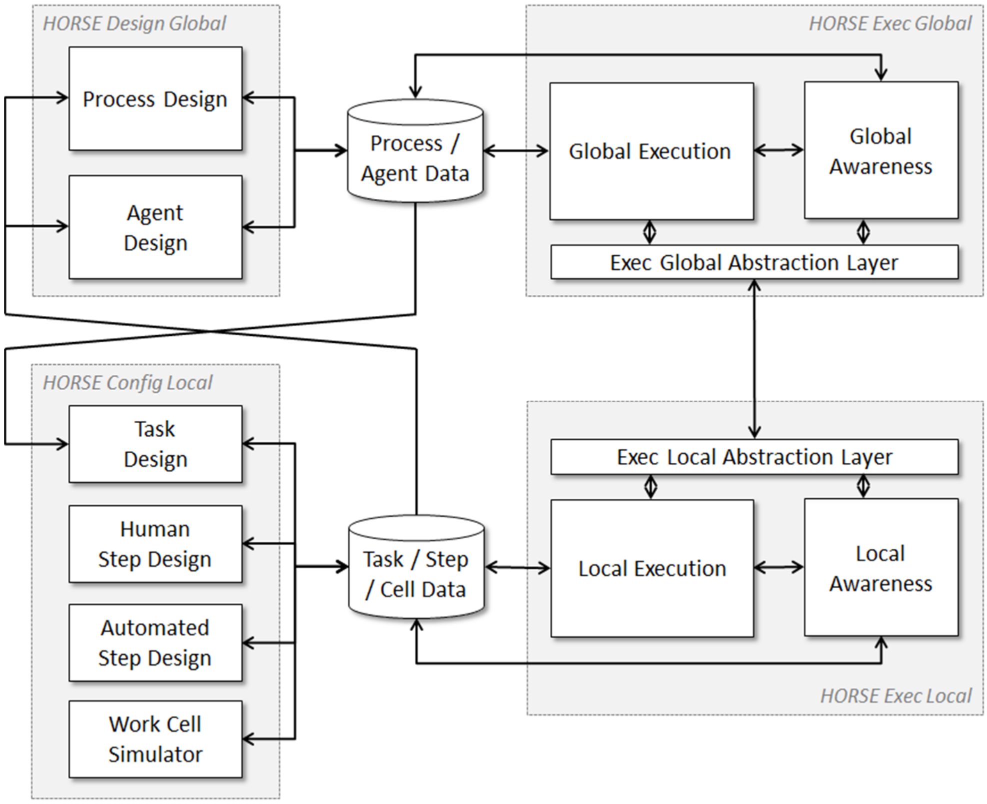

Figure 6. Software aspect of the HORSE System [74].

Additionally, the HORSE System covers the design and execution lifecycle stages of manufacturing activities. Both the global and local system layers are divided into design-time and run-time sub-systems. Processes and agents are defined in the HORSE Design Global sub-system, while tasks and physical constraints are defined in the HORSE Config Local subsystem. The definition information generated during design-time is stored in the two data stores is then utilized during the execution of manufacturing processes [73].

The subsystem labelled 'HORSE Exec Global' is responsible for the orchestration of activities during process run-time. This subsystem is based on an existing BPMS named Camunda BPM, but it is adapted for the manufacturing context. HORSE Exec Local includes the human interface and the control systems of automated agents. This subsystem controls the steps performed by agents and sub-second synchronization between agents. It is an abstract system, with instantiations based on different technologies. In the HORSE Project, the HORSE Exec Local subsystem is realized using Robot Operating System (ROS) and KUKA Sunrise technology. Thus, the control systems of automated agents may run on different operating systems and even follow different control approaches. For example, a cutting-edge KUKA robot and a computer numerical controlled machine can participate in the same process. The interface between the HORSE Exec Global and HORSE Exec Local subsystems is facilitated by middleware, to allow different realisations of the local subsystem. The middleware is outside the scope of this article, but ample information is available in the design documentation of the HORSE System architecture [75].

For this article, it is important to note that process management acts as the central linking pin between the smart technologies, as it orchestrates the activities of the humans, robot and sensors that participate in smart manufacturing operations. As such, the design-time and run-time subsystems of the global layer are elaborated further and shown in Figures 7 and 8, respectively.

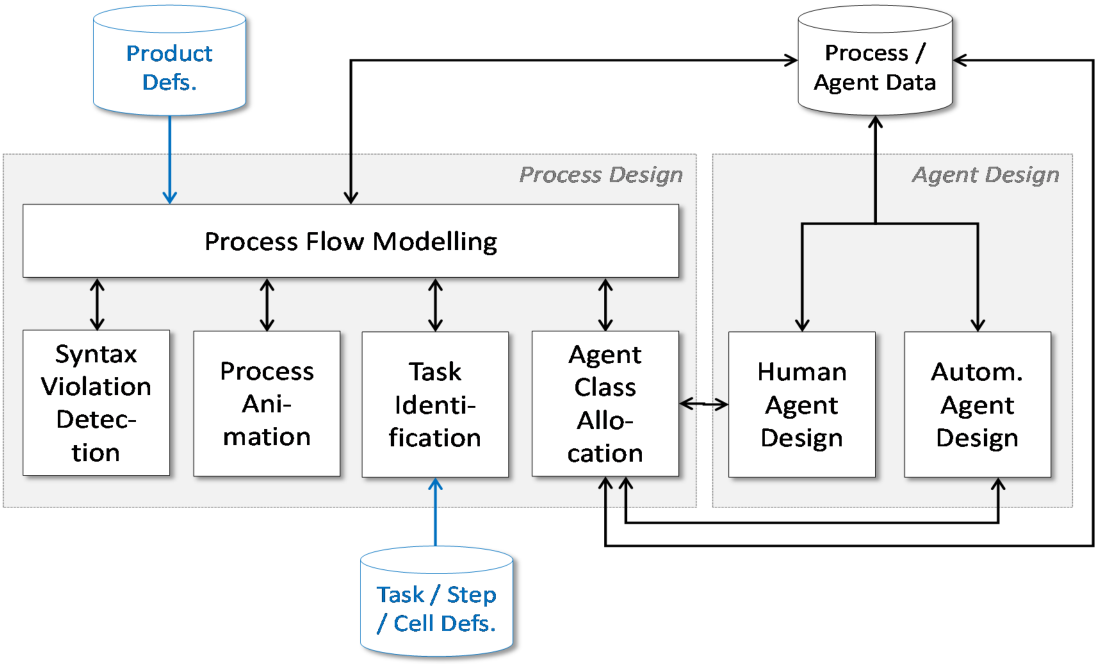

Figure 7. HORSE Design Global subsystem (cf. the upper left part of Figure 6).

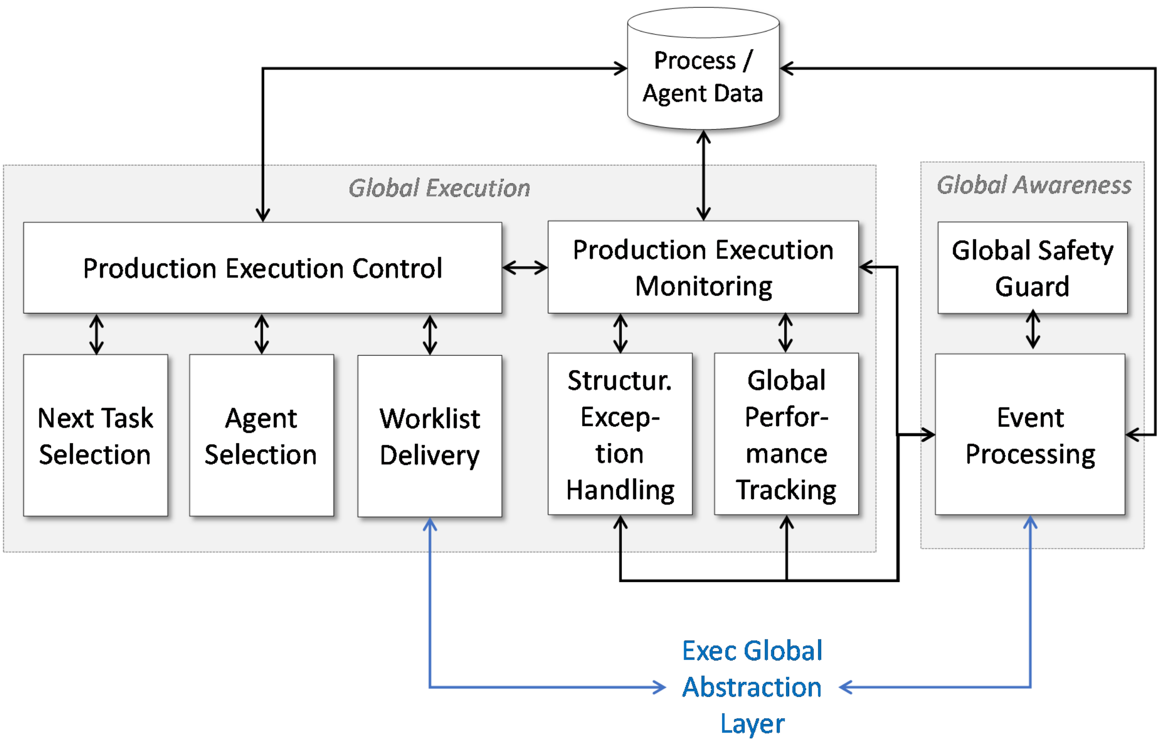

Figure 8. HORSE Exec Global subsystem (cf. the upper right part of Figure 6).

The HORSE Design Global is roughly divided between the process design and agent design subsystems (humans and autonomous robotics are designated as agents). These subsystems can be used independently as needed for the task at hand. The Process Design module contains the functionality to (re-)design manufacturing processes. Results of design activities are stored in the Process/Agent Definitions data store. In case of redesign, the input is retrieved from this database before update. The Agent Design module contains the functionality to define manufacturing agents, i.e., describe their attributes. Product definitions data store is contained and populated in external information systems, typically PLM or computer-aided design software. Task/step and cell data are populated in the local layer of the HORSE System.

The HORSE Exec Global sub-system contains the modules involved in execution and monitoring of manufacturing processes. These modules provide the functionality to initiate tasks based on the process model, assign agents to those tasks and provide the agents with necessary information needed to perform the tasks.

The module named "Agent Selection" is an extension designed and realised in the HORSE Project. This extension was added to the standard BPMS foundation, because additional flexibility is required in smart manufacturing. The agent selection module is a complicated algorithm that selects one or more agents to perform a task, based on the requirements of the task and production order, and the capabilities of the agents. Therefore, this module can dynamically adjust the task assignments based on changing circumstances, if the HORSE System is fed with the necessary information from the factory floor.

Exception handling and performance tracking modules are also included. The Production Execution Monitoring module supports real-time monitoring of manufacturing execution in terms of processes, orders, and agents (human and automated). HORSE Exec Global also includes two Global Awareness modules. The Global Safety Guard is a mechanism that can halt all process execution in case of emergency. Lastly, the Event Processing module is a sophisticated piece of software that attempts to connect seemingly unrelated events in the factory to detect problems before occurrence.

3.3. Practical Demonstration

To ensure practical relevance, the project includes practical cases at ten factories. The factories are part of the HORSE Project consortium, as discussed in Section 2.2. In the HORSE Project, these factories provide first-hand experience of the transition to smart manufacturing. The project extensively utilises the factories to identify scenarios as the representatives of manufacturing practice. Detailed process models were developed by the researchers and accepted by the appropriate factory managers to be used for demonstrations of the HORSE System. The authors documented the evolution from initial observations to executable manufacturing process models in [76].

Table 3 provides a summary of the ten practical cases, with a short problem description and an explanation of the benefit of BPM in each case. Only the TRI case is discussed in detail in this article, but ample information on the other nine cases is given on the project website.

The case study performed at Thomas Regout International (TRI) is the most substantial and significant of the practical evaluations. Located in Maastricht, The Netherlands, TRI is a global leader in the design and production of highly customisable, industrial-grade telescopic slides. Telescopic slides are the components that allow drawers and cabinets to protrude and contract. A typical slide consists out of three metal profiles and two ball-bearing cages. Although a slide only consists of five parts, all those parts can be extensively customised. As a result, TRI can produce approximately 900 variances in the telescopic slides.

Table 3. A summary of the ten practical cases and the benefit gained from the introduction of BPM as part of the HORSE System.

Factory	Scenario Summary	Changes in Horse Project	Benefit of BPMS
Thomas Regout International (TRI)	Assembly of production tools with many thousands of variances.	Process split between transport and assembly tasks.	Assignment and orchestration of human and mobile robot.
Robert Bosch Fábrica de Castellet	Inspection and packaging of variable automotive parts.	Introduce robot to pick part, hold for inspection and place in variable packaging. Camera for inspection.	Orchestrate the actions of the robot and camera, to enable collaborative quality inspection.
Odlewnie Polskie SA, Starachowiche, Poland (OPSA)	Cutting of small batches of heavy, variable parts.	Introduce a large industrial robot and teaching-by-demonstration technology.	Orchestrate transport, handling and cutting tasks.
FLUPOL	Coating of small batch variable parts.	Fenceless collaboration between human and robot. Teaching-by-demonstration for new parts.	Seamless transition between teaching and production process modes. Assignment of collaborative tasks.
Enikon Aerospace	Current automation can only grind 75% of the surface area, resulting in poor process throughput.	Introduce collaborative robots for grinding tasks. Automated quality inspection with a linear scanner.	Orchestration of multiple robots, humans and quality inspection agents.
Ghepi Srl	Manual magnet insertion and quality control dictated by a 45 s cycle time of a moulding press.	Add a collaborative robot to perform some tasks, based on the operator stress level monitored by a heart rate sensor.	Agent selection based on stress level. The robot is slower than the human, but worker health is prioritised.
Tetra Industriservice Group	Production of custom-design, lot-size one metal components made of bent steel pipes.	Introduce a flexible cell based on an industrial robot and standard machines.	Data gained from RFID tags on the product enables detailed process tracking and adjustment.
Tintas Robbialac SA	Manual extraction and transport of material from barrels.	Robot introduced to carry the materials, measure the required quantity, and transport the material through the warehouse.	Orchestration of transport and picking tasks.
Ophardt Belgien	Repetitive manual pick and inspection activities performed by two operators.	Introduction of two robots, a machine vision camera and a conveyor belt.	Process orchestration, including compensation in case of process failure or product defect.

TRI is positively open and transparent regarding its current operations and future directions. This allowed the HORSE Project partners, and this research by extension, to perform expansive interventions across the manufacturing system. Ultimately, the TRI case study is a good indication of the transformation required towards a smart factory. The company published a video about the transformation that it is undergoing, with the HORSE Project as the core of that transformation (https://youtu.be/JBodoko84jc). The HORSE Project team performed several studies and interventions at TRI, but only one such intervention (the tool assembly process) is discussed in this article.

TRI continually seeks to improve their competitive advantage by focusing on the following ideals, while maintaining exceptional product quality:

1. High configurability to produce customer specific products;
2. High manufacturing flexibility to produce small batches, according to customer expectations;
3. Quick response to ensure short delivery times.

The extensive customisation offered by TRI is problematic, with regards to the pursuit of smart manufacturing. Extensive customisation is achieved thanks to two primary mechanisms: skilled employees and configurable manufacturing tools. Although many manufacturing tasks can be automated, it is particularly difficult and expensive to replace highly skilled employees. It is even more difficult to find automation solutions with enough versatility to produce the substantial number of product variances. The reliance on human workers causes several problems in the factory, including the following:

- A general lack of timely information regarding the execution of activities and the utilisation of resources;
- Heavy physical burden on employees who perform manufacturing operations;
- Difficulty to retain or replace highly skilled employees.

The tool assembly work cell is foremost in the operations' management difficulty. Four to eight tools are assembled for each production order, from several hundred parts, with tens-of-thousands of possible combinations. This assembly involves many steps and new personnel undergo several years of supervised training. Incorrect tools can cause devastating loss of production and need for rework, raising the importance of the process.

A prototype of the HORSE System is used to develop executable process models using the industry standard BPMN2.0 [77]. Prior to the intervention of the HORSE Project, the process was linear, following the usual approach of preparation, execution and evaluation, as shown in Figure 9.

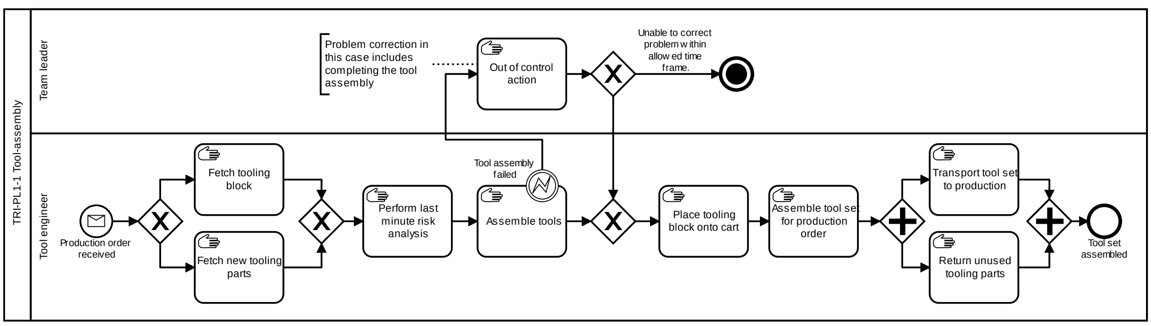

Figure 9. Tool assembly process at Thomas Regout International (TRI), prior to the intervention of the HORSE Project.

The process will undergo significant changes with the introduction of modern technologies in the context of the HORSE project. The following three changes will be made:

1. The task 'assemble tools' will be supported by augmented reality, guiding the operator through the steps of assembling a tool;

2. The task 'fetch tooling parts' will be performed by a mobile robot, allowing the human worker to focus on the assembly task;
3. Introduction of process management technology to orchestrate the activities of the human and robot.

The prototype of the HORSE System is also used to enact the process of the TRI scenario. However, the process model shown in Figure 9 depicts the pre-intervention scenario, before the HORSE Project introduced new manufacturing technologies. In the new scenario, post-intervention, the human operator is assisted by a mobile robot to fetch and return the parts of the tool assembly. The operator is also guided by an augmented reality system that projects information on the workbench. Figure 10 shows a photo of the process in-action and a short video is available online (https://youtu.be/bqTDEZvOdVI).

The photo shown in Figure 10 shows a human operator assembling a tool by following instructions displayed on the workbench. The augmented reality module of the HORSE System generates the images and allows the human to interact with those images by tracking hand movements. Thus, the process management module of the HORSE System can send instructions and receive responses via the augmented reality module. Meanwhile, the mobile robot shown in the background is continually fetching and returning parts based on the progress of the operator. Thus, the process management module is coordinating the activities of the human and robot.

Figure 10. Photo of the TRI tool assembly process, post-intervention.

Figure 11 shows the new process, with tasks spread across two roles for tool assembly and parts transport. The confusing layout is unavoidable due to the dependencies between tasks and page size limit.

The HORSE System is shown to orchestrate the activities of several agents involved in manufacturing operations processes. As part of this demonstration, an enhancement of the HORSE System is also illustrated. The system is equipped with a module that can select the most appropriate agent for a task, based on task requirements and agent attributes. This agent allocation module is a significant extension to a standard BPMS and is discussed in [78].

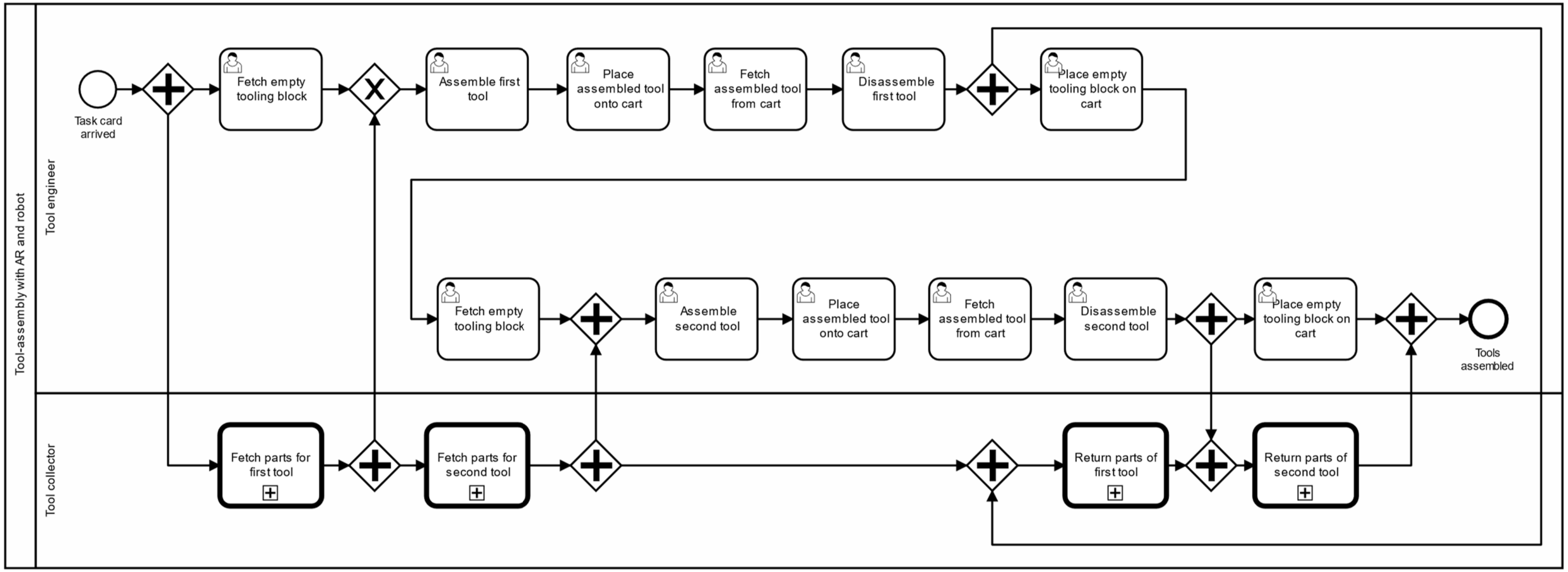

Figure 11. Tool assembly scenario at TRI after introduction of a mobile robot and augmented reality.

Figure 12 shows the duration of eight production runs: four process instances with only the standard BPMS and four instances with the allocation extension enabled. To be clear, all eight process instances are with the HORSE System prototype, but four are without the agent allocation extension. Therefore, all eight instances serve as proof of the HORSE System's ability to orchestrate a manufacturing process with a mobile robot (KMR) and a human operator guided by augmented reality. Furthermore, the four instances on the right-hand side of Figure 12 shows further improvements that may be gained by adding a dynamic selection of agents based on process status. In such a case, the process management system dynamically decides, based on the process status, which agent (a human or a robot) should execute a task. In this specific case, the tasks done by the role 'tool collector' may either be executed by a human operator or by the mobile robot. The system decides on the fly to whom the task will be assigned to, based on the task requirements, agent capabilities, current availability, and the current process status.

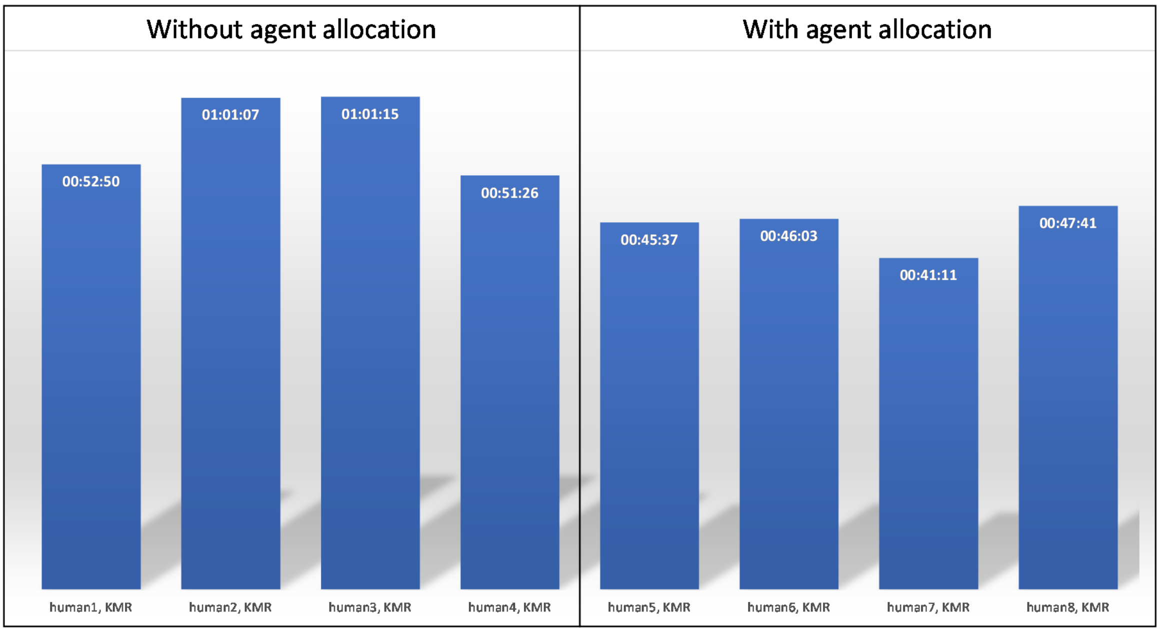

Figure 12. Comparison of the tool assembly process duration comparison without dynamic agent allocation and with dynamic agent allocation enabled.

Although not conclusive proof, the results displayed in Figure 12 do suggest that process improvement may be gained from dynamic selection of agents to perform tasks. This suggestion is in line with the sentiment displayed by [79–81]. Delving into the durations of individual tasks sheds some light on the potential benefits. The results displayed in Figures 12–14 are directly extracted from the event log of the process management module of the HORSE System.

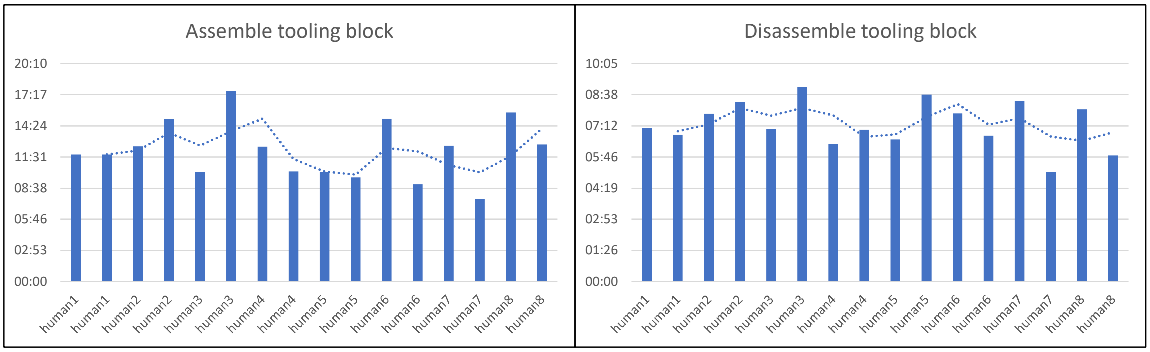

Figure 13. Duration of the assembly and disassembly tasks as performed by different agents.

Figure 13 shows the duration of assemble and disassemble tasks, performed by different agents. No significant difference can be found between the duration of tasks performed by the two groups of operators. Moving on to the fetch and return tasks, the durations are shown in Figure 14. In this case, a clear difference is visible between the fetch and return tasks performed by the mobile robot and the human operator. The difference in process duration shown in Figure 12 can be directly attributed to the difference in fetch and return task duration. Essentially, the agent allocation algorithm determined that the faster fetching and returning performed by the human is sometimes more supportive of the process objectives set by the process supervisor, e.g., in case the human operator is not busy (dis)assembling a tool and available to execute the fetch or return task.

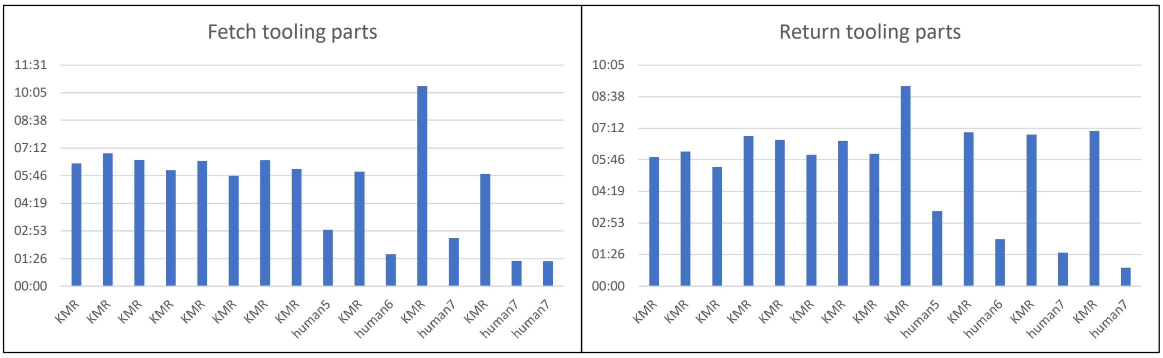

Figure 14. Duration of fetch and return tasks, as performed by different agents.

Although the results obtained from the demonstration are quite compelling, no process performance improvement can be proven yet. The sample size is too small, due to the lengthy duration of a single process execution. Nevertheless, the results do demonstrate that the HORSE System prototype delivers the expected orchestration of several agents and that potential process performance improvements are promising.

3.4. Evaluation

The deployment at the first practical case, TRI, yielded a valuable opportunity to evaluate the acceptance of the system. The Technology Acceptance Model (TAM) [67] is used as both survey and outline for the interviews. The model includes twelve questions, divided into two sections for usefulness and ease of use. Importantly, the questions aim to determine whether the user prefers to use the new technology, compared to the previous way of working. All twelve questions are measured on a Likert scale of one to seven, ranging from extremely likely to extremely unlikely. Figure 15 shows the 7-point Likert scale for the questions.

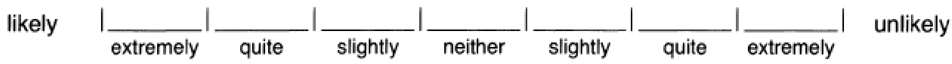

Figure 15. 7-point Likert scale for usefulness and ease of use (1 = extremely likely ... 7 = extremely unlikely).

Nineteen process participants at TRI were interviewed, immediately after the person interacted with the HORSE System prototype. The nineteen people can be broken into the following categories:

- Two experienced tooling engineers;
- Two intermediate tooling engineers (fully trained but not yet experienced);
- Thirteen inexperienced operators;
- Thirteen supervisors.

The 19 surveys and interviews generated significant data to be used for evaluation. Table 4 shows the 12 statements posed to the interviewees and the average rating as reported by the interviewees. The system, as named in the survey statements, refers to the HORSE System, i.e., the collection of HORSE developments involved in the pilot case scenario including the process management and augmented reality solution. As an overview, the system rated favourably, with only two statements garnering a slightly unfavourable rating.

Table 4. Questions asked during interviews with average ratings by interviewees.

Nr	Statement	Average Rating
1	Using the system in my job would enable me to accomplish tasks more quickly.	2.32
2	Using the system would improve my job performance.	2.26
3	Using the system in my job would increase my productivity.	2.37
4	Using the system would enhance my effectiveness on the job.	2.21
5	Using the system would make it easier to do my job.	1.79
6	I would find the system useful in my job.	2.16
7	Learning to operate the system would be easy for me.	1.42
8	I would find it easy to get the system to do what I want it to do.	3.53
9	My interaction with the system would be clear and understandable.	1.84
10	I would find the system to be flexible to interact with.	3.58
11	It would be easy for me to become skilful at using the system.	1.68
12	I would find the system easy to use.	1.79

With 4 representing a completely neutral point on the scale of 1 to 7, none of the questions had a below average overall response. To give some more insight into the range of responses, Figure 16 shows the average ratings and standard deviations for all twelve questions.

The participants were highly enthusiastic of the usefulness of the system. This optimism is often attributed to the procedural nature of the process-centric approach. They acknowledged the value of having a system that encourages disciplined process execution. This is even more important for inexperienced operators, who can be trained faster to participate in complex processes. Apart from increased discipline, some participants also appreciate the lessened mental burden. The augmented reality presents the relevant information, as encoded in the process model, to perform a task and the process automatically moves to the next task, thus making it easier for an operator to follow instructions and perform the work.

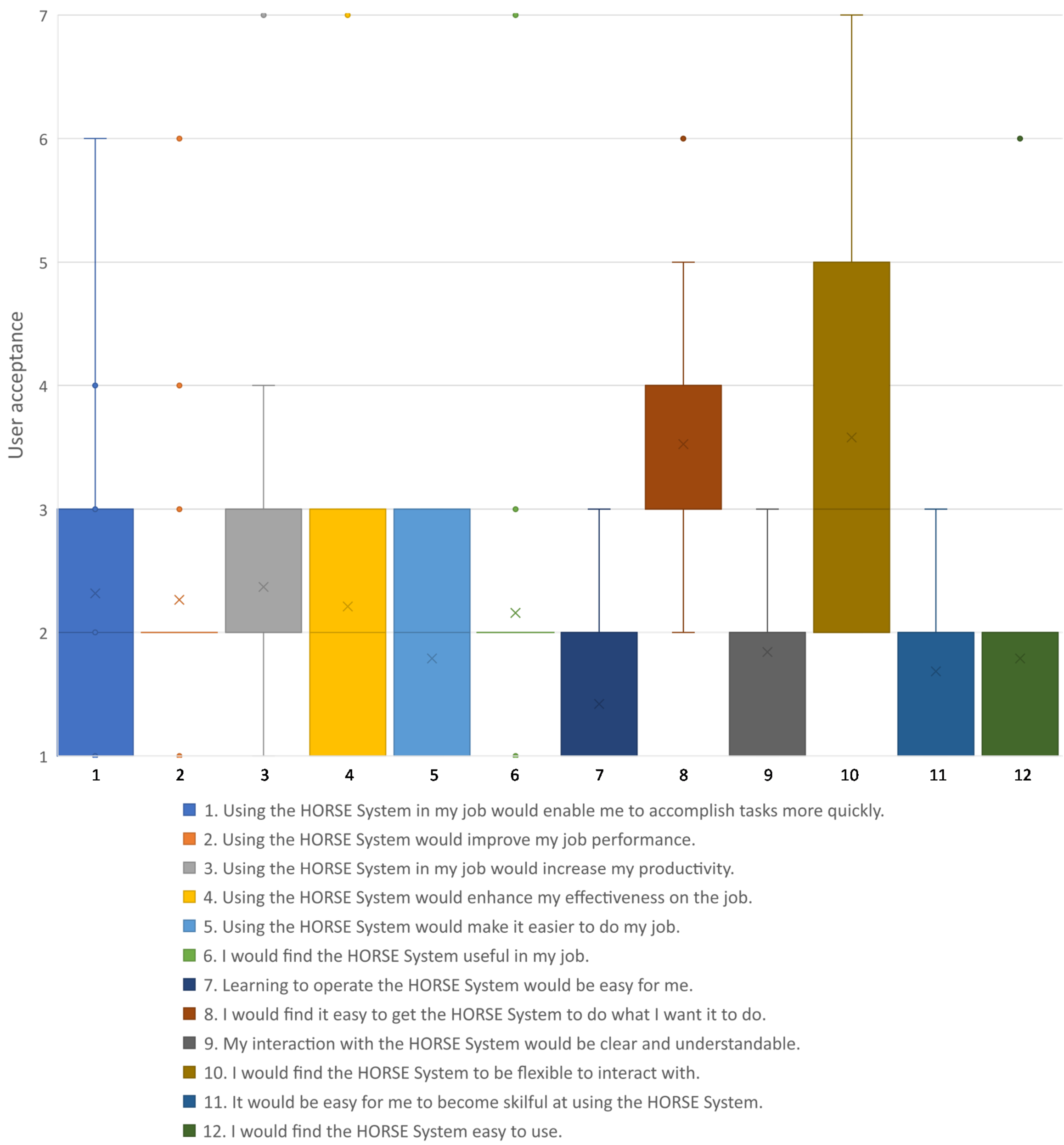

Figure 16. Graph showing the response averages and standard deviations.

A common realisation amongst participants was that they never noticed the mobile robot. The tooling parts were simply available when needed and removed again once the participant finished. This observation points to two positive outcomes. Firstly, the process is well-designed from a physical perspective, because the two agents can operate near each other but do not disturb each other. Secondly, and more importantly, the HORSE System can coordinate two agents well enough for the tooling engineer (the evaluation participants in this case) to allow the mobile platform to work entirely on its own.

The most common complaint by participants were that the system forces them to work a certain way. Manufacturing processes that involve human participants tend to offer some flexibility to the participants on the precise order of tasks. This is no longer possible when the process is controlled by augmented reality and a process management system. This complaint is reflected in the average score of flexibility statement of the TAM, as shown with statement 10 in Table 4 The operators felt restricted and constrained by the system, minimising their opportunity to pursue process improvement. This is a matter of process design and task definition. If more autonomy is needed, fewer details can be specified on the task level. The process design capabilities of the HORSE System are highly flexible and can accommodate users who want more autonomy. Perhaps this can be used as motivation for multiple variations in a process, based on the profile of a user. A more experienced user can be given more informative guidance, rather than restrictive guidance.

The second most common negative observation, especially as perceived by the more experienced participants, is related to deeper understanding of the process by the operator. The experienced operators remark that an executable process will make it less important for operators to consider why the process is performed a certain way. They will simply perform the work, as instructed by the system. This presents two possible problems: 1) when something goes wrong, the operators are less likely to respond appropriately, and 2) the operators will offer less ideas for improvement, because they are not engaged to consider deficiencies in the process. This sentiment is again reflected in the questionnaire, as shown with statement 8 in Table 4. While this criticism is fair, it is again a matter of the information presented to users. The practical part of the evaluation, with users performing the process as guided by the HORSE System prototype, only presented limited process-related information to the users. The evaluation was technology-driven, to see how users interact with and accept the technology. However, the information-display were somewhat neglected in favour of the augmented reality system. The HORSE System is perfectly positioned to present rich process-related information to the user, given that it also manages the upstream and downstream processes. The user can be presented with status information about upcoming cases and inform the user about activities that will happen subsequent to the current task.

4. Discussion

The problem statement defined in Section 1 is the following: Current manufacturing process management techniques and technologies are not well equipped for the flexibility needed in Industry 4.0. It is proposed that BPM knowledge can be applied to alleviate the stated problem. The HORSE System is positioned as a reference architecture for a manufacturing operations management system for smart manufacturing. The reference architecture complements a BPMS with several new technologies, including collaborative robotics, augmented reality and situational safety awareness. A prototype of the HORSE System is used to demonstrate the exaptation of BPM in smart manufacturing, by performing the following activities:

- Modelling of manufacturing processes by using a standardised business process modelling notation;
- Enacting manufacturing processes populated by humans, robots, other smart devices, and conventional machines;
- Selection and assignment of agents for tasks, based on task requirements, agent capabilities, agent availability, and process status;
- Monitoring of process status and performance based on information provided by all agents.

A HORSE system prototype was deployed for practical demonstration at ten factories across Europe. The prototype was deployed and demonstrated in real manufacturing facilities lending credence to the maturity of the HORSE System architecture. The factories were not only hosts, but also collaborators [82], with an active contribution to the success of the HORSE System. With ten successful demonstrations completed, the project team considers the HORSE System at technology readiness level 6 [56,57]. The expectation is that software vendors should leverage the principles and knowledge established in the HORSE Project to envisage new manufacturing operations management tools and techniques.

The demonstrations show that BPM techniques and technologies can be used to design and execute smart manufacturing processes. Beyond the viability of process management in manufacturing, the realized system yielded other benefits in the test cases. The system supports integration between levels 2, 3 and 4, which can be thought of as vertical integration.

Furthermore, the system also enhances integration between various instantiations of level 2, i.e., horizontal integration. The process management system of the HORSE Project is connected to level 2 systems based on different technology, including ROS and KUKA Sunrise. Coupled with direct interfaces to humans, the system can enact cross-functional processes by orchestrating the activities of any agent in an enterprise. More interestingly, it is easier to allocate agents from one business unit to assist elsewhere. For example, if an automated vehicle fails to transport items from the warehouse, the receiving operator can be directly informed of the problem and instructed to fetch the items. Previously, the vehicle would be controlled by the warehouse management system while the operator receives instructions from the manufacturing execution system. To summarise, the demonstrations showed the following potential benefits:

- Cross-functional process integration across business management and manufacturing operations;
- Vertical integration from business processes to individual human and automated agents;
- Improved process flexibility from run-time allocation of agents to tasks based on task requirements, agent capabilities and process status information.

Regarding the notation used in this research, BPMN represents a trade-off. Indeed, García-Domínguez et al. [23] compared BPMN2.0 with VSM and IDEF3 in terms of the modelling of activity sequences, timing constraints, resource assignment, material flow and information flow. The study found that BPMN2.0 is comparable to IDEF3, with the addition of process participants, event handlers and message flow; however, BPMN2.0 lacks the ability to model the physical aspects of a manufacturing system. As for VSM, BPMN2.0 is found to be complementary, because VSM is more concerned with the flow of material and information, rather than the exact sequence of activities. The more important advantage of BPMN is that it includes an execution semantic. IDEF and VSM are adequate analysis and improvement notations, but BPMN can be used to enact processes with a BPMS.

Witsch and Vogel-Heuser [83] also compared BPMN to other notations, but rather as the foundation for the formal specification framework of manufacturing execution systems (MES). BPMN compared favourably to flowcharts, petri-nets, Unified Modeling Language (UML) and Systems Modelling Language (SysML) This effort resulted in extensive modification of BPMN, to cater for the specific requirements of the considered cases. Similarly, Zor et al. [84] present BPMN extensions for manufacturing processes, but these are again specific to the single case study.

BPMN is clearly a candidate for manufacturing process modelling and enactment. It has been considered from various perspectives, including as the formal execution semantic for an MES and as a modern replacement for IDEF3. However, these considerations are somewhat ad-hoc and disparate. This research shows direct evidence for the use of BPMN for manufacturing by using a BPMS to orchestrate the execution of manufacturing processes supported by smart technologies.

Furthermore, the open and standardized nature of BPMN brings additional benefit. By using international standards and open-source software, the process management system is extendible and adaptable. Companies can change the system to suit their needs or opt for a different system with the same notation. Additionally, adopting an international standard notation brings substantial embedded knowledge. BPMN enjoys extensive academic and commercial support and interest, which will see it evolve and improve over time. This status is particularly beneficial for recruitment purposes. The pool of professionals or consultants with BPMN knowledge and skill is larger than any proprietary notation.

Lastly, a shortcoming of the current HORSE System realization is its interaction with other information systems. The HORSE Project team considered integration with common enterprise information systems such as enterprise resource systems (ERP) and manufacturing execution systems (MES). However, to keep the development confined to the integration of emerging technologies, the HORSE System was designed and implemented without (automated) interfaces to other information systems. This is considered as future work, because it is not expected that a system akin to the HORSE System can be implemented in isolation. In fact, it is quite possible that the principles embedded in the HORSE system architecture will be absorbed into other information systems. The process management portion of the system is a prime example. It is acknowledged that process management is a core component of many MESs. The HORSE System is not expected to replace MES, but rather show how BPM knowledge and technology can enhance or complement a conventional MES. It is not difficult to contemplate how processes are initiated in the process management system in response to scheduled triggers in the MES.

Apart from the expected benefits gleaned from the practical demonstrations, the project team also encountered and overcame several challenges. The following lessons are noted:

- Variability in a process represents a technological challenge, but it also complicates the implementation. For example, augmented reality software must be loaded with the visual information to generate the images;
- Surprisingly, the digital delivery of information represented a revolution for some factory personnel, regardless of the other benefits of smart manufacturing;
- BPMN, as the modelling notation, can be unintuitive for factory personnel. The notation does not have specific symbols for common manufacturing concepts, such as queues and staging.

5. Conclusions

The manufacturing industry is experiencing unprecedented disruption. Fluctuating demand and mass customization compel factory managers to look for new ways to improve manufacturing flexibility. A manufacturing system must be able to rapidly adapt its operations to produce small volumes of highly variable products. Fortunately, several emerging technologies are anticipated to deliver the flexibility that is so eagerly awaited. More intelligent and versatile industrial robots can perform the larger variety of actions necessary to produce more product variants. Handheld devices, augmented reality and collaborative robotics enhance the already considerable proficiency of highly skilled factory workers. The ubiquitous connectivity promised by the Internet-of-Things and cloud computing enables improved insight into the state of the manufacturing system and the ability to quickly react to changes. It is expected that mass-customized products will be produced by smart robotics in dynamic processes managed in the cloud [85].

The new technologies, while promising, introduce a new set of problems to the factory. New technologies invariably require new knowledge and skills. Incompatibilities with existing systems and practices in the manufacturing system are also inevitable. Apart from incompatibilities with existing systems, the new technologies are also not available as a single, integrated package. In fact, the absence of out-of-the-box solutions that combine the different technologies are considered a primary impediment on the path towards smart manufacturing [86].

The HORSE System is such an integrated package. It is built around the principles of business process management, enhanced with connections to smart technologies, including advanced robotics and augmented reality solutions. The architecture of the HORSE System is presented as a reference architecture for a modern manufacturing operations management system in the age of smart manufacturing. The reference architecture can serve as starting point to integrate BPM with emerging technologies to develop a manufacturing operations management system for smart manufacturing. The implementation of a HORSE System prototype at ten factories serves as practical demonstration of the use of BPM in smart manufacturing. The HORSE System is built around an open-source BPMS and adapted for the manufacturing domain. Foremost of the adaptations is the development of an agent allocation module. This module can select and assign one or more actors to perform a task, based on up-to-date information about the actors and tasks. This extension to the process management capability of the HORSE System affords the manufacturing system significantly more flexibility to deal with fluctuating demand and highly customized products.

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