

# Reconfigurable Manufacturing Systems Characteristics in Digital Twin Context

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**Abstract:** The concept of a reconfigurable manufacturing system (RMS) has been introduced to enable production systems to continuously evolve and respond rapidly to unpredicted and fluctuating market environments. To achieve this goal, RMS needs to exhibit six core characteristics: modularity, integrability, scalability, diagnosability, convertibility and customisation. These characteristics are required to ensure manufacturing systems' resilience while maintaining productivity and quality. Assessing these characteristics at both the design and operating phase can be aided by the digital twinning (DT) of physical systems. To this end, the DT-RMS concept is introduced in this paper as a dynamic cyber-replica of the physical production environment, enabling a high-level of transparency about data, performance, and relevant reconfiguration decisions. As a result, DT-RMS responds to the need to integrate requirements and performance targets for the RMS characteristics at design and operating-time.

*Keywords:* System Architectures, Reconfigurable Manufacturing Systems, Digital Twins.

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## 1. INTRODUCTION

Reconfigurable manufacturing systems (RMS) aim to address the need that a production environment should be equipped with sufficient agility to meet rapid changes in market demand (Koren et al., 1999). Whether at design, or at operating time, the ability to assess the impact of such agility on production performance is of critical importance for an enterprise. Digital twin (DT) concepts are particularly relevant to this end, enabling such assessment to be made at both design and operating time (Negri et al., 2017). While there is a growing body of literature on DT for core manufacturing concepts and processes, there has been limited attention jointly on DT and RMS. Part of the literature focus is mostly on the role of simulation in DTs (Cimino et al., 2019). A further viewpoint is looking at the data flows between the physical asset and its digital counterpart (Kritzinger et al., 2018). A real time view of DT highlights the role of connectivity (Liu et al., 2019), which enables operating time data flows (Kritzinger et al., 2018) in a Cyber-Physical System (CPS) setting (Alam & El Saddik, 2017). Importantly, connectivity itself is further considered as an enabler for data, processes, and services flows at operating time, which may include simulation, optimisation, and real time monitoring and control (Tao et al., 2018)(Tao et al., 2019). Furthermore, the storage and management of the evolution of the digital version of a physical asset in the form of a digital thread is increasingly pursued (Saracco, 2019). Yet, research outcomes on joint design and operating time DT in a way that connects a DT concept with real time production reconfiguration ability execution has been limited. The present paper targets this area by proposing a design framework for integrating RMS concepts within a manufacturing environment. The framework is based on key RMS characteristics and the interrelationships between them and how these can be expressed in a DT.

The rest of this paper is organised as follows: Section 2 discusses related work regarding core characteristics of RMS and expectations regarding DT technology in manufacturing.

Section 3 analyses structural similarities between RMS characteristics and places DT concepts within an integrated view of a manufacturing enterprise. The DT-RMS framework is introduced in Section 4, highlighting interactions between its components. Section 5 is the conclusion.

## 2. RELATED WORK

While research on DT in manufacturing has seen an explosive growth, the focus in this paper is specifically on DT for RMS. When making the connection between design and operating time RMS concerns, then relevant research is positioned in the area of Cyber-Physical Systems (CPS) and in manufacturing, Cyber-Physical Production Systems (CPPS) (Monostori et al., 2016). The interest is therefore on work related to key characteristics of RMS, which should be of relevance to their digital twinning and on implications for DT in Manufacturing.

### 2.1 The Six Core Characteristics of RMS

Henry Ford's Model T assembly line marked the advent of the mass production era. High productivity and low cost made Dedicated Manufacturing Lines (DML) a very effective way to fulfil stable demands. However, since DML could not satisfy increasing requirements on product and production variations and Flexible Manufacturing Systems (FMS) is constrained in balancing capacity ramp-up and equipment investment, RMS concepts were introduced to provide a high-volume medium-mix solution (Koren et al., 1999). RMS aimed at structural changes capabilities, both in hardware and software, in order to handle unpredicted market fluctuation, introduce new product families, and maintain quality and throughput at balanced costs. To meet these requirements, five defining characteristics of RMS were highlighted, namely modularity, integrability, customisability, convertibility, and diagnosability (Koren et al., 1999). The capability to handle demand fluctuation and throughput ramp-up is emphasised by including scalability in the RMS core characteristics (Koren, 2006). The characteristics are outlined in Table 1.

Table 1. Six Core Characteristics of RMS

Feature	Description
Modularity	Division of functions into modules that can be modified for best arrangement between different production schemes
Integrability	Ability to swiftly and accurately combine function modules through physical and information integration
Diagnosability	Capability to monitor the RMS state to determine root-causes of defects.
Scalability	Capacity to expand or shrink production capacity by adding or removing manufacturing resources (e.g. function modules) and/or replacing components.
Customisability	Focused flexibility to adjust RMS to diverse single product families
Convertibility	Capacity to transform current system functionality to meet production needs.

The approach employed a laboratory manufacturing line (iFactory) to test reconfigurability of new system layouts and processes, and the capability to plan the manufacturing of a variety of products. The latter demonstrates convertibility as the capability to fast adjust new products and enable quick production changes. Part family formulation or customisation is described as the most crucial action in RMS design (Khanna & Kumar, 2019). Modularity and integrability are summarised as the most fundamental design-oriented hardware and software aspects (Koren et al., 2018). Hardware RMS components can include modularised machines for machining or assembling, material handling for part transportation, and inspection machines for quality control. Reconfigurable inspection machines provide in-process diagnosability, which aims at quality control and continuous improvement (Koren et al., 2018). Mathematical modelling for the six characteristics allows them to become part of the decision making for RMS (Koren et al., 2018), making it essential for inclusion in DT.

## 2.2 Digital Twins in Manufacturing

It is considered that the DT concept could trace back to lunar exploration tasks in the 1970s when engineers tried to find a solution for operating spacecraft by testing a subaerial physical backup. In 2010, the availability of a relevant NASA roadmap marked a new era for the application of DT concepts in a range of applications (Shafto et al., 2012). Internet of Things (IoT) technologies in production environments was considered a significant breakthrough. It enabled moving away from early views of DT, which focused purely on simulating the actual physical system. With IoT connectivity it became possible to incorporate real time data flows from the physical asset to its digital shadow (DS) and eventually to allow bi-directional data and control flows back to the asset itself (Kritzinger, Karner, Traar, Henjes, & Sihn, 2018)(Tao et al., 2019). The management of the evolution of the digital counterpart of the physical asset via a digital thread is now also increasingly included in DT implementations (Saracco, 2019). The capabilities of digitalisation enablers have therefore made the DT concept a mainstream vision for manufacturing practice. This can have very profound implications for the future practice of RMS. A static digital model (DM) in CAD or a

comprehensive mathematic model, can both include descriptions of its actual or planned physical counterpart. However, such static information cannot be transformed to make its physical twin an active component in a highly dynamic system. For example, a parameter-driven sheet-metal CAD model could generate multiple variants in a short time but its impact on production scheduling or quality fluctuation could only be summarised and recorded in retrospective. By adding an automatic feedback data route from the physical asset back to its digital representation, the latter becomes an active Product Lifecycle Management (PLM) representation, which offers interactive and customised product views, and become the interface with different PLM phase activities. DS with digital continuity could accompany its physical twin through its whole lifecycle and keep generating data for further analysis (Kaewunruen & Lian, 2019). Upgrading a DS to a full-function DT can be then enabled via a supervisory control and data acquisition (SCADA) enabled manufacturing system. A SCADA system provides the ability of real-time control and hence empowers online adjustment. The DM and DS stages focus on three main aspects: decision making through engineering and statistical analyses (Gao et al., 2019); health analyses for improved maintenance and planning (Liu et al., 2019), and digitally mirroring the life of the physical entity

## 2.3 Challenges for RMS DT Research

Demands for smart production and mass customisation resulted in research and development efforts that have led to broadening the understanding and use of DT. One view identifies four applicability levels, namely for manufacturing assets, people, factories, and production networks (Lu et al., 2020). This opens up possibilities for twin-twin interaction within a system of systems approach (Dietz and Pernul, 2019), facilitated by ideas from software, hardware and systems design for RMS. Past research focused on RMS to solving hardware and software modularity and integrability design aspects (Napoleone et al., 2018). Other research on DT focused further on production planning and control (Kritzinger et al., 2018). However, RMS has no explicit roadmap to guide designers and operators to achieve RMS performance targets within a DT approach. Research on the joint handling of RMS and DT is still limited. The motivation for this paper is therefore to establish an expandable framework that highlights how RMS core features could be consolidated within DT.

## 3. RMS CHARACTERISTICS AND DT STRUCTURE

### 3.1 RMS Core Characteristics Relationships

The evolving structure of hardware and software brought significant challenges to the design and operation of RMS. Seamless data flow and reactive mechanical components help to address some of these challenges as DTs are employed within CPS. By abstracting the RMS core characteristics (Napoleone et al., 2018) framework, a simplified structure of the six characteristics relationship is presented in Fig. 1. The colour convention is orange for design characteristics, yellow for system ones, and green applies to customisation. The design characteristics, modularity and integrability, enable system modules to be independently modified.

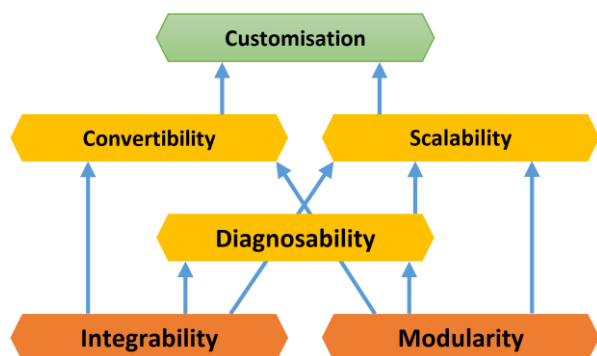


Fig. 1. RMS Characteristics Interrelationships

Convertibility, scalability and diagnosability are affected by the two primary characteristics (Napoleone et al., 2018). Diagnosability has more complex influence than the other characteristics as it implies different meaning depending on context and timescales. In most early RMS works, defect root-cause finding ability is an essential part of diagnosability. To achieve this goal, diagnosability usually relies on a Reconfigurable Inspection System (RIS) (Shang et al., 2020). RIS is a subsystem consisting of a group of quality assurance modules based on Stream of Variation (SoV) theory and it tackles the quality issue in productivity ramp-up stage. Convertibility and scalability are relevant to machinery adjustments, route adjustments, and layout modifications, i.e. they are system-level characteristics. Customisation is affected by these system characteristics and a DT for RMS would need highlight the relationship among them. Simultaneous design of a new module and its DT would aid the assessment of the interaction of a module with other parts of the RMS and their overall contribution to the characteristics. This possibility creates the basis for amplifying the contribution of design characteristics to system-level ones. This is applicable to all physical entities of RMS, including human actors. For instance, a DT for operators would reflect their working condition and well-being through real-time interaction and tracking. Legacy or uniquely designed machinery with hardware or software interfaces would enable its inclusion within an overall DT, upgrading their modularity and integrability (Lu et al., 2020). Even if physical modularity and integrability remain mostly unchanged, convertibility and scalability are boosted by digitalisation enablers, including data acquisition mechanisms.

### 3.2 Manufacturing System and DT Structure

When considering an operating time view of a manufacturing, a plant control viewpoint (ISA-95 architecture) is appropriate (Fig. 2). CPS encapsulate human and non-human actor activities and data flows, flattening the system architecture and making tasks and goals explicit (Hofmann & Rüsçh, 2017). This makes interfaces between layers transparent, allowing agent objects to handle seamless data flow (Leitão et al., 2016)(Zhang et al., 2017). A DT for the operating time view of a manufacturing environment would need to map the various components of such an architecture. While individual component DTs can reside at multiple layers, a natural choice would be to position the DT in between the cyber-physical and the enterprise layer, so as to offer a digital view of operations, while abstracting the lower tier components.

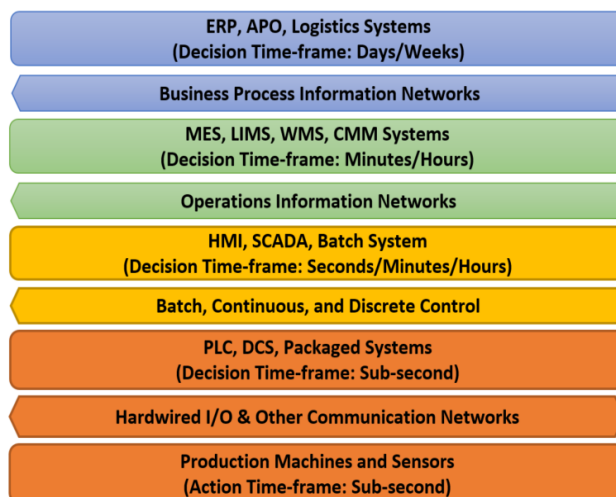


Fig. 2. Manufacturing Plant Layers

The DT layer mediates the information that needs to be exchanged between the user application layer and the lower tiers, which compose the CPS, as abstracted in Fig. 3. It enables non-hierarchical data flows, making the hierarchical structure less clear, increasing overall system transparency. A DT would bring together the abstracted modular software and hardware components, enabling seamless data flows, and as a result, more informed monitoring, decision-making, and control. Modularised hardware and software are therefore indispensable from the concept of RMS.

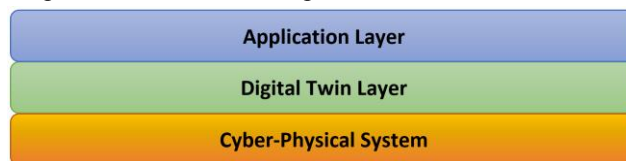


Fig. 3. Digital Twin Layers

## 4. RMS-DT Framework

Utilising elements from both ISA 95 and DT representations, a four-layer CPS interactive framework is introduced for a DT-enabled RMS, based on the structure of RMS characteristics. These layers include the Physical Execution and Sensing Layer (PESL), Autonomous Control Layer (ACL), monitoring and management layer (MML), and knowledge service layer (KSL) at the top. PESL and ACL construct a CPS at field level. MML presents as a digital shadow (DS) at factory-level. KSL takes all long-term jobs at enterprise-level. This framework highlights the core RMS characteristics throughout the system architecture and is illustrated in Fig. 4.

### 4.1 Bridging Physical and Digital Worlds: PESL & ACL CPS

The blue section represents PESL. It is the physical foundation of the digitised RMS. This layer focuses on several key features: hardware modularity, hardware integrability, and production customisation. Led by needs for production customisation, manufacturing module designers should pay particular attention to the integrability between new and old modules. As an evolutionary system, RMS can start at a basic manufacturing layout with fixed machines. This can be considered an upgrade of dedicated manufacturing lines.

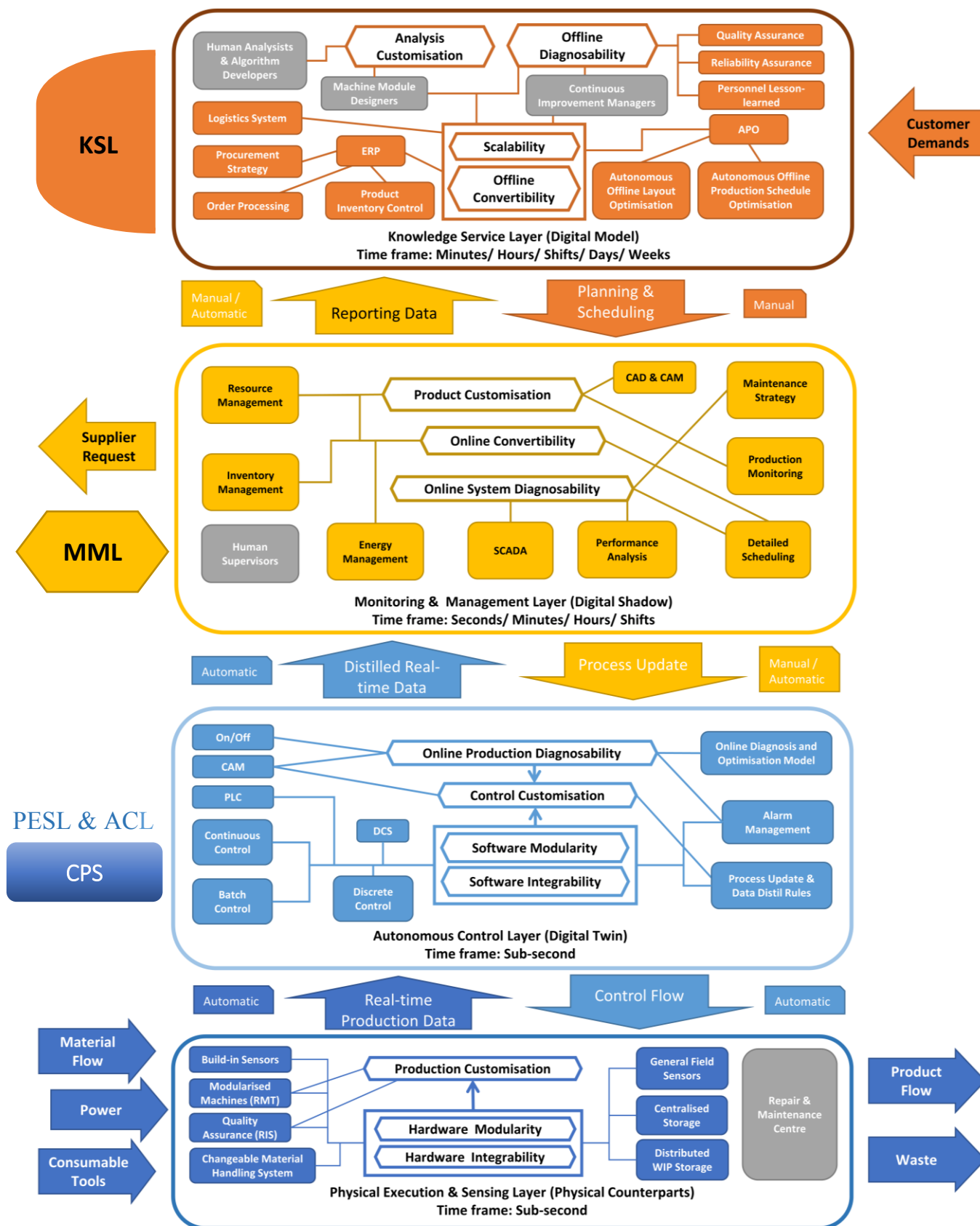


Figure 4. A Digital Twin RMS Design Framework

RMS modules should include reconfigurable machine tools (RMTs), modularised machines, changeable material handling system, distributed work-in-process (WIP) storage buffer, and centralised storage. Modularised machines should be equipped with product and process monitoring sensors to determine the process and production asset condition. Other sensors can offer readings needed for quality and performance monitoring. Overall, sensors can monitor work-in-process (WIP) in the machine modules and update customised product DTs in ACL and MML. Based on dynamically updated execution orders from ACL, machine modules could be monitored, thus increasing production diagnosability, while reducing quality inspection and production rework time. A well-designed machine module should improve production customisation, hardware modularity, and integrability. Processing routes, machine module quantities and positions, and material handling system (MHS) need to be flexible. Limited product families can have specific pick-up structures or fixtures. MHS should be the connecting thread between tailor-made components and universal intralogistics. MHS could include changeable components (e.g. robotic, AGVs) and need built-in sensors. Grouping and analysing data produced by sensors would enable more transparent production lines and enable bottleneck predictions. Distributed WIP and central storage can share similar structure but do not need built-in sensors. Operators could be abstracted also as digital representations of physical entities. Based on maintenance schedules from KSL, off-work modules can enter into maintenance status.

PESL and ACL construct a field-level CPS and data exchanges take place at the ACL layer. This CPS dominates material and control flow and pushes information flow to upper layers. The hardware carriers of ACL reside in proximity to PESL entities, or even inside them. The time frame of ACL is closer to PESL, which makes it appropriate for edge computing and online production diagnosability. This characteristic is the first line quality control mechanism. Real-time analytics can guide decisions regarding whether the system should reconfigure a CAM programme, raise an alert for quality check, or whether to shut down machines or system in an emergency. All such actions are enabled by software modularity and integrability. Real-time production data may come from different suppliers. ACL processes raw data from PESL and may trigger alerts or control actions. Non-alert data are sent to MML. Control customisation is necessary for ACL. In most cases, software modularity and integrability could be provided by a well-designed universal framework. However, deviations from expected behaviour may disrupt the original structure. In this situation, customised controls can be included in the DT-RMS.

#### *4.2 Virtual Entities & Autonomous Behaviour: MML*

MML is a comprehensive interface close to human operators at the field level, presenting active data via visual interfaces, controls and dashboards. When an automated decision is considered inadequate, human supervisors could manually adjust the machine by sending an order to ACL. The time scale of MML is consistent with higher level operations and management. Modularised machines and MHS modules in PESL are modelled as individual twin agents in MML. Hierarchical distributed architecture and assets acquire new

digital representations as customised twin agents in MML. These agents receive updates of distilled data from ACL and push them further for analytics in the KSL layer. Real-time status at MML could be monitored either inside the system or remotely. MML constitutes an upgrade of traditional SCADA and Management Execution Systems (MES), with added diagnosability. Customisation is influenced by modelling, monitoring and resources management. Product models and ACL data flows can drive performance analytics. In MML, diagnosability is the result of the cooperation among units and dynamic correcting actions when a product family is fixed. Online diagnosability involves scheduling updates, and repair and maintenance recommendations, and ACL data analytics. MML features autonomy convertibility to handle product family changes, based on resources agility and rescheduling.

#### *4.3 Continuous Evolution: KSL*

In this framework, KSL is considered as a human-system collaborating space where a group of “twins of twins” offer larger scale digitisation of a physical “System of Systems”. It enables making the system predictive and proactive. KSL at enterprise level translate customer requirements, especially engineering and manufacturing-to-order requests, into detailed plans and schedules to be sent to MML and sets aside near real-time requirements to MML and ACL. KSL focuses on application-level services and knowledge-based advice. Reactive models and algorithms for convertibility and system diagnosability are developed and tuned KSL. Both external and internal to the system factors can change the convertibility and scalability of RMS. For instance, product updates can generate requirements for new machine modules or technical upgrades. Continuous improvement managers helps balancing new modules and product performance. Unexpected demand fluctuation could lead to throughput adjustment. Convertibility is limited by centralised scheduling; and scalability attracted even less attention. In this way, convertibility and scalability make RMS hard to manage and affect other characteristics, namely scalability and offline convertibility.

Enterprise resource planning (ERP) and advanced planning and optimisation (APO) respond to the resource allocation and optimisation within a traditional ISA 95 structure. With the aid of flexible cloud computational resources access, KML can identify a way to consolidate convertibility and scalability. Offline diagnosability focus on product quality and system reliability assurance in KSL. By testing different simulation-based solutions on the digital copy of MML, an appropriate solution can be found and sent to MML without concerns for negative production effects. Unlike PESL and MML, human analysts rather than algorithms or algorithm developers play vital roles in KSL. Analysis customisation focuses on limited product families comparing individual approaches. As a non-real time function, KSL could also outsource analysis jobs to a third party. Pre-developed autonomous offline layout or schedule optimisation strategies can drive continuous improvement and operational excellence of RMS-DT system. At the same time, the comparison between these existing strategies and new strategies can involve cloud resources outside the framework for better performance.

## 5. CONCLUSION

This paper presents a novel framework for designing a DT-enabled RMS. Six core RMS characteristics are mapped. Implementing such a framework can positively impact on manufacturing functions. Production and control can be supported in sub-layers at both the design and operating phase via hardware software Modularity and Integrability. Human-system interaction is empowered by supporting diagnosability. Communicating flows between physical resources include equipment, devices and humans. At PESL, engineers and operators have a functional interface with the manufacturing system. The ability to penetrate CPS barriers of DT-RMS will release operators from continuous real time supervision. At the highest layer, KSL, schedulers can assess production plans using simulation tools. Designers can consider design characteristics for components, assets or systems and assess their interactions. System architects can map data flows and function blocks. Every action would leave a footprint on a DT-RMS. The arising digital thread will help continuous evolution of the RMS core characterises. Further research is needed towards establishing quantified RMS performance indicators. Simulating models and real-world case studies are needed for a thorough assessment. Pilot implementation instances will take the assessment to the level of physical testing and validation to guide the development of real applications.

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