Remanufacturing Data Space – a vision to favour circularity

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Abstract: Remanufacturing represents an effective approach to the circular economy, pursuing several sustainability principles, mainly related to the economic and environmental spheres. However, realizing a production environment completely dedicated to remanufacturing is very challenging for companies interested in this business: the high investments needed, the uncertainty on the quality of the products to remanufacture and the still low acceptance of remanufactured products by end-users represent some of the barriers that a company has to face when dealing with remanufacturing. This paper aims to propose a possible approach to address some of the aforementioned barriers. Leveraging on the use of modern Information and Communication Technologies, the logics and tools for the realization of a Data Space Ecosystem (DSE) dedicated to remanufacturing are presented. Within the DSE, different remanufacturing stakeholders (companies acting as remanufacturing service providers and end users or clients) can interact, favoring the collaboration among companies through data/information exchange and resources/assets sharing. This should allow for a reduction of investment costs and other benefits for companies, based on a raise of knowledge on the remanufacturing processes, which can be, in some cases, very difficult to carry out efficiently.

Keywords: Remanufacturing – Data Space Ecosystem – Circular Economy - Sustainability

1. Introduction

Remanufacturing (RMfg) has become an effective and sustainable operational strategy to deal with environmental, social and economic issues regarding the utilization of natural resources (Yang et al., 2023). RMfg is one of the alternatives for reprocessing used products at their end-of-life/end-of-use (Eionet, 2021). RMfg facilities restore used products (cores) to their " as good as new" condition by re-conditioning or replacing their worn and damaged components (Manco et al., 2023). To do so, acquired cores are sorted, cleaned, disassembled, inspected, and, finally, remanufactured (Guide Jr, 2000). RMfg processes enable a considerable reduction in virgin material utilization, energy requirements, and CO2 emissions (Yanıkoğlu & Denizel, 2021) while diverting tons of products away from landfills. The result of such a process is that remanufactured products are high-value goods that can be sold in the primary market at a lower price. RMfg market was raised during the last decade and it is projected to grow by 2030 dramatically. Despite the great interest and the positive market forecasts, there are still economic and technical barriers to transitioning from linear to circular economy models. Possible investors in RMfg see the pay-back point very far in time, along with a great risk of generating financial losses (Ayati et al., 2022). Technical barriers are the most important for companies that aim to join the RMfg business. The need for big investments for realizing dedicated RMfg production environments and the high-uncertain supply chains still represent a risk to consider by stakeholders. The quality of returned products directly influences the complexity of RMfg operations and their efficiency, generating many uncertainties, especially regarding the economic convenience of the RMfg process itself. Moreover, many consumers still consider that the quality of remanufactured goods is lower than the new ones, and most people are not aware of the environmental benefits of the RMfg process (Li et al., 2017). A viable solution to address these challenges and mitigate risks is to improve cooperation among industries, by encouraging information sharing and increasing resource interoperability. This study proposes the use of a Data Space Ecosystem (DSE), namely a cloud-based digital environment, for enabling the Remanufacturing-as-a-service (RMaaS), which allows for transforming RMfg resources into services that can be exploited by multiple stakeholders. DSEs can manage a variety of data formats and applications from multiple systems (Data Diversity and Accessibility Property) and provide integrated functions for searching, querying, updating, and administrating the variety of data (Franklin et al., 2005; Moreno et al., 2023). The proposed DSE is advantageous because it will allow an interoperable use of production capacity among RMfg stakeholders (big companies, SMEs and end-users) and the decentralization of the execution of processes within a trusted environment. The goal is to build an environment that is able to collect data from the servitised resources located in the shopfloors and to manage these information (maintaining the sovereignty of the owner) to reduce the entry barriers towards the RMfg business mentioned above. The DSE will enable collaboration among RMfg companies and provide clients with a trusted environment in which easily searching for RMfg services. Indeed, the necessity of having dedicated environments for RMfg will be mitigated by the sharing of RMfg resources and information from different providers.

In this context, the use of some enabling technologies is mandatory. To successfully develop the RMfg Industry, emerging economies must utilize the potential of IoT technologies to move forward in a sustainable circular economy (Chau et al., 2021). The enabling technologies for the RMaaS are Cloud Computing (Caterino et al., 2022) and the IoT (Caterino et al., 2021). They will be crucial for developing digital representations of physical resources (Digital Mirrors) and, thus, to allow resource servitisation. Moreover, the introduction of innovative digital tools, such as the Digital Product Passport (DPP) (Jensen et al., 2023), could represent an opportunity to better monitor the life cycle of products. Cloud technologies have been exploited in many industrial sectors and are applied in manufacturing through Cloud Manufacturing (CM)(Liu et al., 2018). CM research projects mainly dealt with the issues of the adoption of the cloud paradigm in the industrial production systems, addressing the problems of digitalisation of the manufacturing environment and leading finally to the "-as-a-Service" paradigm (servitisation of processes and resources). DSEs can be a solution to address such a need for data sharing (Runeson et al., 2021). Dataspaces are an abstraction aimed at overcoming some problems encountered in data integration systems; their main purpose is to allow the sovereign and secure exchange of data within a "trusted ecosystem" involving multiple players. The remainder of the paper is as follows: Section 2 presents the relevant literature on the use of the required technologies to enable the concept of RMaaS, while section 3 presents the model proposed in this paper, with a focus on all the requirements towards the DSE. Finally, section 4 concludes the paper.

2. Literature review

Resource servitisation represents a fundamental step for enabling RMaaS as it allows the DSE to be aware of the capabilities of the shared resources. Opresnik & Taisch (Opresnik & Taisch, 2015) found that servitisation is beneficial for RMfg as it increases customer satisfaction, reduces operational costs and increases the competitive advantage of both the provider and the consumer. Landolfi et. al (Landolfi et al., 2019)outlined the architecture of a platform in the Manufacturing as a Service (MaaS) domain to support data sovereignty in the sustainability assessment of manufacturing systems. An ecosystem was created to fully exploit production capacity. The platform allows the automated acquisition of manufacturing data, their elaboration through an LCA-based tool and the aggregation into KPIs that are useful for further decision-making processes. Kerin & Pham (Kerin & Pham, 2019)made a review of emerging industry 4.0 technologies in RMfg. They found that there is a lack concerning the study of the connection of cyber-physical systems to the IoT to support smart RMfg. Moreover, the study underlined the need to align the evolving information and communication infrastructures and circular economy business models. Hasan & Starly (Hasan & Starly, 2020) proposed the architecture of a Cloud Manufacturing-as-a-Service platform. The research provides the design, implementation and validation of middleware software architectures whose goal is to link client users with manufacturing service providers. Caterino et al. (Caterino et al., 2022) suggested a framework to explain the logic of cloud RMfg and describe its main features. The framework was tested and the mathematical model concerning the activity scheduling in cloud RMfg was validated for an industrial scenario. The problem of task assignation optimisation in the cloud RMfg environment was first approached by adopting the Bees Algorithms (Caterino et al., 2023). Tang et al. (Tang et al., 2012) built a cloud service platform for a closed-loop supply chain oriented to manage RMfg operations. The platform empowers the service-oriented manufacturing and management of the product life cycle by combining Industry 4.0 technologies, such as cloud storage, cloud computing, cloud security and IoT with the company's management system (information collection, analysis, integration and optimization). The management of activities within a DSE requires the presence of advanced Manufacturing Execution Systems (MES). It is needed for enabling the monitoring of the shared resource and leading the production process according to the current operative state of resources and achieving an optimised scheduling of activities through a dedicated orchestrator tool. Tariq et al. (Tariq et al., 2024) proposed an IoT-Enabled Real-Time Dynamic Scheduler in an Industry 4.0-Based Manufacturing Execution System that they named MES 4.0. The application of the methodology confirmed that the presence of real-time systems updated from IoT devices enhances the performance of scheduling decisions. Wang & Wang (Wang & Wang, 2014)introduced a novel service-oriented RMfg platform based on the cloud manufacturing concept for the recovery of Waste Electrical and Electronic Equipment (WEEE). Their Cloud-based RMfg system aimed to establish a smart and interoperable platform that realises a "Request-Find-Provide" service loop based on service-oriented architecture. The QR code was utilized as an information management mechanism to strengthen the readability of the products during system implementation. IoT allows the collection of valuable data regarding the operational status of the machines. Challenges and barriers to be faced during the implementation of an Industry 4.0-based RMfg system have been discussed (Chau et al., 2021; French et al., 2018). GAIA-X (Braud et al., 2021), born as a European project initiated to enable secure, open and sovereign use of data, is the European reference for European dataspaces. It aims at building a trusted, sovereign digital infrastructure for Europe and defines a global architecture for the European digitalised ecosystem. Regarding manufacturing, CATENA-X (Schöppenthau et al., 2023) is one of the main projects that addresses the topic in such a context, trying to integrate the manufacturing concepts in the global ecosystems. It is an integral component of the GAIA-X project focused on the automotive sector. with many services oriented to sustainability, but definitively still oriented to linear economy. Notably, capacity management issues related to RMfg operations might be non-trivial. Also, sustainability restrictions need to be considered, due to process variabilities arising from processes that are a holistic sum of many operations performed by different stakeholders. To reinforce the company's resilience, when facing such risks, a business model that exploits the unused production capacity has to be adopted, thanks to the sharing of servitised resources, controlled based on critical variables to success. According to the analysis of the state-of-art, there are no solutions that can effectively address the need for a dynamic RMfg system, to which an SME can easily access, even if there are the technological basis and the organisational contexts that enable the definition of such a solution.

The DSE for the RMaaS presented in this study attempts to merge and improve the past achievements regarding digitalization, virtualisation and servitisation of RMfg systems. Unlike the previous DSE, it is oriented to the CE. The innovation is the design of a DSE based on cloud principles, IoT and other Information and Communication Technologies (ICT) to enable a trusted environment where several RMfg stakeholders can get access to create cooperation and collaboration, achieved through resource and information sharing. The ultimate goal of the model proposed is to increase the competitiveness of RMfg companies by reducing entry barriers, especially linked to huge investments required to build sustainable facilities.

3. The proposed model for Remanufacturing Dataspace

The model proposed in this paper is an evolution of the framework proposed by Caterino et al. (Caterino et al., 2022) in which the concept of cloud RMfg was developed to create a distributed network of RMfg resources, centralized managed, to improve the overall RMfg process and reduce the entrance barriers to this business for the stakeholders. The framework provided by Caterino et al. gave a general overview of the solutions needed to apply the concept of cloud in RMfg activities and of the benefits of developing such a distributed system. In this paper, an operative solution for that framework is found in the realization of a Dataspace Ecosystem (DSE), proposed as a mean for achieving collaboration and interaction among different stakeholders (RMfg service providers, clients, etc.), i.e. for enabling the concept of Remanufacturing as a Service – RMaaS. This will favour industrial interoperability and the exploitation of unused RMfg production capacities. Industrial interoperability will be guaranteed by the sharing of useful information on the RMfg processes, which will generate knowledge on them, and by the collaboration among different RMfg resource providers to realize complex RMfg processes. Each resource provider participating in the DSE will be enabled to share only the available production capabilities and capacities, thus exploiting the possibility of adopting unused resources. This is a win-win strategy for all the stakeholders: clients of the DSE, i.e. those interested in purchasing one or more RMfg services, will have a dedicated environment in which searching for the required service; service providers have visibility within the DSE and can be paid by clients for providing a RMfg service; furthermore, when accomplishing a RMfg service, the information about the provided service, the quality of the remanufactured product and others are recorded within the DSE in order to favour the future RMfg services on the same product or family. To realize such a complex system, data sovereignty and an adequate level of security in data exchange must be ensured, as well as a feasible procedure to servitise resources, namely associating real resources to the services proposed in the DSE. Thus, a number of elements are required to enable such a DSE. A general methodology is presented in this paper to achieve such a purpose and it is represented in Figure 1. In order to better understand the idea behind the proposed model, one can think of the following scenario: a client, i.e. a physical person or a company, wants to remanufacture a core. After registration in the DSE, the client inserts some information related to the characteristics of the core, that will concur to build a RMfg work cycle. Based on the work cycle, a scheduling module (part of the orchestrator in Figure 1) is run to find feasible solutions with different times and costs of execution, matching the required services with those shared in the DSE by resource providers through servitisation. The scheduling information is sent to the client, who can decide to accept or reject the solution identified. In case of rejection, other solutions are elaborated until acceptance by the client. Once the RMfg process has started, the progress will be visible to all the involved stakeholders, thanks to the information gathered from an advanced MES (next-generation – ng – MES in Figure 1). If a problem occurs during the RMfg process execution, the system will find alternative solutions and notify the client, which can decide to change the value chain configuration or stay with the current one, accepting the new conditions. Given the distributed nature of the RMfg process proposed in this model, also the logistics services must be considered as part of the process. Executing such a complex decentralized RMfg process will require that companies move towards the use of digital and ICTs technologies to share information and to realize a digital mirror or a digital twin of the resource (companies will always maintain the data sovereignty for the resource shared). Such information will also be used for monitoring the ongoing process, but also to build KPIs such as the planned downtime, the unplanned downtime and the overall equipment effectiveness (OEE) on the resources involved. This will allow companies to monitor their performances and the DSE to update the information on the shared resources to improve the orchestration of activities of future processes. Moreover, the information on the executed RMfg process will be registered in a DPP available within the DSE. This will favour interoperability because companies will have access to knowledge on the RMfg process of the product and will also favour the continuous circularity of the product, thanks to the information about the historical interventions made on that specific product. In the following, the single phases to realize the DSE are depicted.

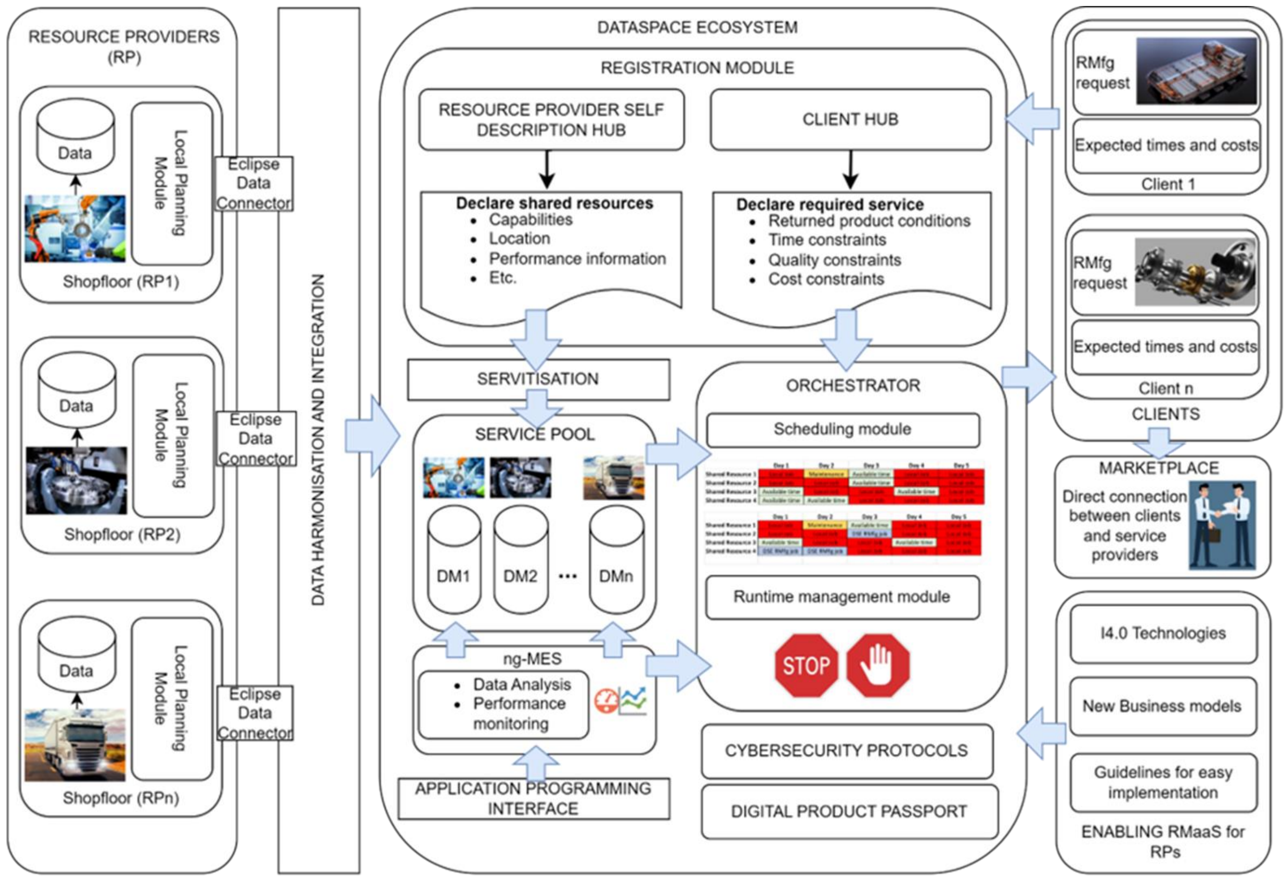

Figure 1: the framework of the Remanufacturing Data Space Ecosystem

3.1 Remanufacturing operations characterisation

The baseline for achieving the concept of RMaaS is a correct characterisation of RMfg activities. This step is needed to create a unique correspondence between the actual RMfg operation or process to realize and the services offered within the DSE. For a correct characterisation of RMfg operations, 3 steps have been identified as necessary in this model:

1. Identify all the inputs of the RMfg process, both physical and measurable, like the Bill of Materials and the type of resources needed to realize the process, and non-physical or non-measurable, like the skills required for that process.
2. Create a flowchart to illustrate the working cycle. In the flowchart, each phase of the process must be clearly characterised by highlighting all the inputs and resources needed for it.
3. Identify all the critical parameters and variables that affect the outcome of the process. RMfg processes are strongly affected by uncertainties due to the quality of the returned items. Thus, the most uncertain process variables are also the most critical and their identification helps in taking the process under control.

In the proposed model, once a RMfg process has been established and validated for a product or a family of products, it is recorded in the DSE and made available to all the registered stakeholders.

3.2 Servitisation

Resource servitisation represents the basic step to enable RMaaS because it allows to represent the shared resources within the DSE, making them available for usage. Resource servitisation can be divided in 2 main phases:

1. Virtualization: it is responsible for the creation of the virtual models that will encapsulate resource capabilities. For example, a RMfg cell may be described by formal models that reproduce the main cell functions, while capability can be represented using semantic models.
2. Servitisation: it is responsible for associating real resource information with the virtual models, transforming the information into something with a standard format that is readable by the DSE.

These two phases allow the DSE to have information on the shared resource, such as the type of job that a resource can accomplish, the location, the cost, the cycle time of the resource and many other information used for optimize the task assignation to resources. All the information on the servitised resources is stored within the DSE in a service pool.

3.3 Advanced version of Manufacturing Execution System (ng-MES)

In order to monitor the resources shared by service providers within the DSE, an advanced version of the classic Manufacturing Execution System (MES) must be deployed. This system is needed to get real-time information on the shared resources and make them available to the DSE with the aim of being always informed on the status of resources and the ongoing RMfg process. For instance, a basic set of functionalities of the MES for the DSE should allow to: i) monitor the progress of a work order, including its intake, start, and completion; ii) record the execution time of a work order; iii) record information on who or what performed the work order; iv) record the list of tasks and/or spare parts used to perform the RMfg task; v) display the current operational status of production resources (available/unavailable). All this information will be used to have full control of the RMfg process under execution and potentially take immediate corrective actions if some problems arise.

3.4 The orchestrator

Resource servitisation is needed for associating RMfg tasks to resources, based on the capability of resources to accomplish such tasks. The concept of RMaaS, explicated through the DSE, realizes a decentralized RMfg process, in which several resources, located in different places, accomplish different tasks. Thus, a complex RMfg process is decomposed into tasks and there is the need to associate such tasks with services, namely the shared RMfg resources, to complete the RMfg process. The optimized scheduling of RMfg tasks and the control of tasks in due course are the main focuses of the orchestrator. In the proposed model, the orchestrator is made of 2 modules:

1. The scheduling module, devoted to optimizing the scheduling of RMfg tasks based on the specific objectives of the clients and the information associated with the resources through the servitisation process and retrieved from the advanced MES. In fact, the possibility of scheduling a task on a resource is not only constrained to the capability of a resource to perform the task, but also to its performance on the specific task and the local jobs on which the resource is involved, i.e. those jobs not deriving by the DSE.
2. The runtime management module, which is devoted to monitoring the tasks once they have been scheduled on specific resources. In case any problem occurs during the execution of a task and some delays are created, this module registers the information and can send an alert to the clients and to all the other stakeholders involved in the RMfg process.

The orchestrator has the scope to find feasible and optimized scheduling for the RMfg process to accomplish and monitor the ongoing tasks to ensure that no problems arise during the process execution.

3.5 The Digital Product Passport (DPP)

RMfg processes can be difficult to manage because of the variabilities related to the products to remanufacture. To help in reducing these variabilities, the model presented in this paper proposes to create a DPP for every new product remanufactured within the DSE. The DPP contains useful information on the product itself, like the components replaced due to their low quality, the time in which RMfg process was carried out and the type of operations performed on it. This information will help providers of the RMfg services in the RMfg decision-making process and will enable transparency by tracking the overall process execution. In this way, a future RMfg of the same product will be easier for remanufacturers. Moreover, the use of a DPP will also generate benefits for clients, who will have full knowledge of their remanufactured product, with information on the component replaced or repaired, the date of RMfg and others.

3.6 The Data Space Ecosystem (DSE)

The DSE represents the place in which stakeholders interact to create a distributed network for sharing knowledge, information and resources, based on the concept that cooperation may be beneficial for all. According to the specific focus, the architectures of DSEs can be different. In the case of the DSE for RMfg, the architecture must contain at least the following elements:

1. An identity management using self-sovereign identity principles to exchange identities and certifications of any kind among participants.
2. A self-description hub allowing companies to describe their specialisation as a "claim", with the possibility to get a certification by an independent "trust anchor".
3. A semantic hub, allowing to create a full alignment in the usage of terminology between the different stakeholders of the DSE.
4. An Eclipse Data Connector (EDC), a way of securely exchanging data over a data space.
5. A marketplace containing the services that are available with each of the contributing remanufacturers.
6. Digital Agent deployers, using Infrastructure-as-Code components allowing to easily deploy infrastructure pieces, containing the protocols to exchange data among them easily.

Other elements can be added to the architecture based on the specific necessity of the model. For example, a specific infrastructure for connecting Digital Mirrors of the resources directly from the providers should be foreseen in the case this capability is necessary for the DSE.

3.7 Enabling technologies

The realization of the RMaaS concept requires the use of enabling technologies towards the DSE. Digital technologies represent the key point to offer RMfg resources as services. Cloud technologies represent the base: they ensure the abstraction of resources through the realization of Infrastructure-as-a-Service (IaaS) through Infrastructure as a Code (IaC) and Platform-as-a-Service (PaaS). IaaS provides virtualised resources over the internet and delivers some fundamental infrastructures, such as virtual digital mirrors, storage and networking, by means of some key features that allow scalability and flexibility, needed to adapt to changing business requirements and for customising resource capabilities according to client's needs. PaaS allows to manage the complexity of handling infrastructures, thanks to the application of methods and libraries that accelerate the development process and services for databases, messaging, caching, and more, reducing the operational burden on developers and simplifying administration. The Internet of Things is another needed technology. In particular, it is useful for data collection by means of sensors that allow to gain insights into the operational status of the machines, identify potential issues and optimise production processes, tracking the movements of the products to be remanufactured. Digital Mirrors (DM) are necessary to acquire information related to the real resource represented and use them in a static way for simulating the RMfg process before the real scheduling of activities by the orchestrator. Cybersecurity is needed to protect sensitive manufacturing data and intellectual property and ensure the integrity of the production process, while always maintaining data sovereignty. Other technologies that may be needed include: Augmented Reality (AR) to train workers on RMfg activities, collaborative robots to integrate automation that will enhance efficiency, flexibility, and speed, and blockchain for secure and transparent supply chain management. All the useful technologies must be supported by appropriate ICT infrastructures..

4. Discussion

The concept of DSE has become popular in recent years and many platforms were born to enable communication and collaboration among different people with a common objective: GAIA-X, CATENA-X, MANUFATURING-X, Manufacturing Data Spaces. The DSE for RMaaS aims to be the next one. However, some requirements are needed to realize it. First of all, developing knowledge: i) knowledge about the technologies, such as digitalisation, servitisation, ICTs; ii) bringing people be aware of the possibility of collaboration that a decentralised ecosystem offers; iii) knowledge about remanufactured products and CE. Users need a specific DSE for RMfg purposes. The RMfg operations and processes are sensibly different from the manufacturing ones. Thus, specific digital representations and services for this purpose are needed to let users to easily access the desired market sector. The designed DSE satisfy the users' needs to exchange data and guarantees them the sovereignty of their own data. Users need fast response times to ease the reconfiguration of their production systems. To exploit DSEs, it is important to guarantee a reliable and fast response from services offered by the DSE. The main plus of DES for RMaaS, when compared to previous DSE, are: (i) it is specific for RMfg but may also cover other production scenarios, (ii) it offers a frictionless experience to the user facilitating the digital transition, especially for SMEs, (iii) it guides the SMEs and big companies in the path towards the digitalisation finalised to the servitisation, (iv) it is a significant enlargement of the services offered by other DSEs, considering circular production strategies, (v) it gives a set of services to each SME that covers some major issues in planning and control of the operations through a digital approach to production management. However some barriers have to be mitigated to fully exploit the DSE. Most of the RMfg companies are SMEs with a lack of technologies to enable servitisation and participation to a DSE. Thus, minimal requirements to move companies towards the DSE are mandatory. The selection of modern technologies to enable RMaaS in classic RMfg factories to let them move beyond the boundaries of the factory itself is a prime requirement. The Lack of standardised procedures to carry out the RMfg processes on different products still is a great barrier. Moreover, RMfg and logistics activities carried out through the use of the servitised resources in the DSE must be optimised.

5. Conclusion

In this paper, a novel model for enabling the concept of RMaaS has been presented. With the aim of favouring the spread of RMfg as a candidate production process to favour a circular economy, this paper proposed a model to decrease some of the entrance barriers to RMfg based on the realization of a DSE. The DSE should favour information sharing and interoperability, two fundamental aspects for the success of the RMfg business. However, the realization of such a DSE requires the use of many tools and technologies from different fields, such as informatics and operations management. Thus, its realization must be opportunely studied, and a cost-benefit analysis is necessary to evaluate the effectiveness of the proposed model. The lack of this analysis and the lack of a real case study represent the main drawbacks of this paper, but also a starting point for future research on this topic.

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