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Procedia CIRP 122 (2024) 641–646

www.elsevier.com/locate/procedia

31st CIRP Conference on Life Cycle Engineering (LCE 2024)

Information process-system modelling for Circular Economy of manufacturing systems

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Abstract

Recent push towards sustainable development have lead machine tool builders to begin adopting novel business models which are usually peculiar in product-service-systems. In particular, business models as 'pay-per-use' introduced the issue of rental of production capacity integrated with the management of the life cycle of assets in a Circular Economy perspective. However, when it comes to machine tool builders, the high degree of customization of capital goods and in particular of multi-stage automated assembly systems that are strongly linked to the characteristics of the final product make this solution more difficult. Hence, the implementation of such business models represents a clear challenge for machine tool builders and manufacturing system suppliers from technological perspective. This work discusses preliminary results in the technological implications of such strategy. A real industrial case related to cross-sector multi-stage automated assembly systems is presented to highlight the technological challenges and potential research directions.

Keywords: Manufacturing systems; Sustainable development; Knowledge management; Servitization.

1. Introduction

Sustainable development have pushed companies to seek for novel business models for pursuing Circular Economy (CE) of products, thus reducing the consumption of resources [1, 2]. Successful examples show the validity of the CE goal with respect to traditional linear business models for manufacturing companies [3, 4]. Within this evolution, servitization of products have played a major role by leading many companies to provide product-service-systems, rather than the pure product [5,6]. In this way, the manufacturer retains ownership of the product and its embodied resources and thus carries the responsibility for the costs of risks and waste [7]. On the other hand, the customer pays only for the needed service and not for the physical product which is often not of interest for its core business. One of the first examples has been Rolls Royce selling flight hours instead of its engines, or office printers [8].

This type of business models, where the product may be recovered for multiple circular use, is typical in sectors where products are quite standards and may be used without particular differences by one customer or another [9].

However, when the product itself is customized, it is not easy to perform one of the typical circular activities for the end-of-life management, i.e. reuse, repair, remanufacture by upgrading, recycle whether in the same sector or in a different one. This is the case of manufacturing systems, which can be considered as products manufactured by machine tool builders for specific customer needs. As a consequence, the problem of circular life-cycle of manufacturing systems began to be addressed only quite recently [10].

In this work, a preliminary analysis of this problem is discussed, with respect to real industrial case studies. The consequences of circularity for manufacturing systems, in particular automated assembly systems, is shown by means of an information process-system model at relational level, and by means of physical solutions, at technology level.

10.1016/j.procir.2024.02.018

2. Description of reference industrial case studies

In this Section, two automated multi-stage manufacturing systems (MMS) are presented, in order to be used as reference for the discussion on circular MMS and information modelling at process-system level.

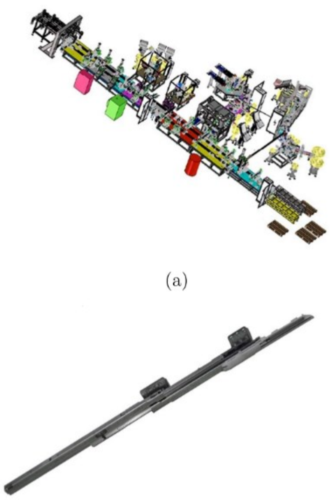
The two MMS are designed and manufactured by the same machine tool builder. The company designs and produces assembly systems that can find application in various sectors, such as electro-mechanical, automotive, accessories for furniture, appliances and electronics. The structure is typical of B2B (Business to Business) and for single orders: the MMS offered and sold are customized on the specific needs of the customer, therefore unique. These characteristics are peculiar of one-of-a-kind production, hence the implementation of novel Circular Economy business models represents a clear challenge in such sector. In the following, the two very different MMS are analyzed, to provide the preliminary foundation for the successful implementation of Circular Economy. Only non-sensitive information have been disclosed. Therefore, not all data are provided for the analysis of the proposed case study, but only the relevant ones.

2.1. Drawer slides assembly line

In the make-to-assemble furniture sector, production volumes are extremely high, therefore assembly lines are required to have high throughput and high efficiency. Moreover, production variety must be considered as competitive factor. Fig. 1 shows the multi-stage assembly line (a) to produce the full-extension drawer slides (b).

Each drawer slide is composed of 78 components to be assembled through various operations. The assembly line has a target throughput of 700 parts/hour and it is customized to produce up to six different product types with required production change time of about 1 hour.

Interestingly, the production life-cycle of such MMS lasts for approximately five years, i.e. after five years re-design of furniture due to technologies, safety, new material, pushes for the manufacturing of new products requiring new MMS.



(a)

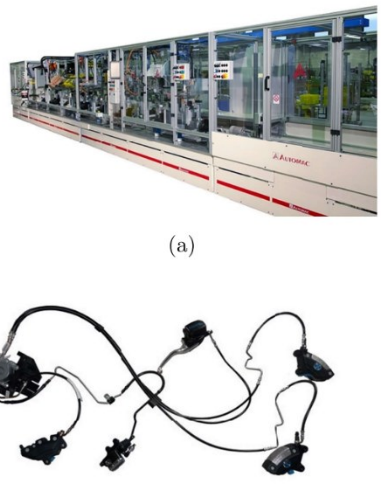
(b)

Figure 1. Multi-stage assembly line (a) for full-extension drawer slides (b).

2.2. Motorcycle brakes assembly line

In the automotive sector, some product types require extremely high quality standards for safety reasons. Motorcycle brakes are part of this group. Fig. 2 shows the MMS (a) for the assembly of motorcycle brakes (b). Each brake is composed of 15 components. The assembly line has a target throughput of 24 parts/hour and it is customized to produce up to five different product types with required production change time of about 5 minutes.

Similarly, the motorcycle brakes depend on the re-design of the whole product, i.e. the motorcycle. Equally in this case, the life-cycle of the product is quite short and the MMS must be frequently replaced for technological updates.



(a)

(b)

Figure 2. Multi-stage assembly line (a) for motor-cycle brakes (b).

2.3. Modularity as driver for circular MMS

The two assembly lines described so far may seem quite different in terms of product type and components, as well as performance. On the other hand they share similar dynamics in the respective sectors, such as various product types, frequent product redesign hence changes of production, requirements of data gathering system for the better operations of the MMS [11]. A multi-stage automated assembly system is usually composed by multiple process stations, i.e. 'modules', performing basic operations on material and components to obtain the final assembled product, as shown in Fig. 3. These operations may include riveting and screwing, welding, stamping, inserting and pressing, fastening and clinch riveting. In between process stations, according to the defined configuration, buffer spaces decouple the modules, usually in the shape of linear rails for accommodating pallets. Pick and place modules may also be part of the MMS, in order to handle parts especially when a change of positioning is needed in the assembly plan. Moreover, feeding systems as rotary or vibration tables provide the necessary consumables as rivets, screws, hinges and other minor components needed to assemble the final product. Last but not least, inspection stations are usually placed at the end of the MMS or in key locations, in order to verify that the sub-assembly or the final assembly is correct. Inspection stations may include vision-based systems, laser-based systems or simple functional testing as leak testing and similar.

In this context, the key driver is the modularity of the MMS. Indeed, the MMS can become a circular product, hence going through multiple lives only if value retention strategies are applied, i.e. each module can be reused easily. In order to do so, the integration of the modules in the MMS shall aim not only to a plug-and-produce strategy, but also to easy unplug-and-reconfigure strategy. With respect to the MMS previously described, an analysis was performed at the company premises,

Figure 3. Example of process module: orbital riveting station.

analyzing a subset of already configured assembly lines for diverse sectors, as assembly of electromechanical components, mechanical components for automotive, components for furniture sector, and for healthcare. Each assembly line was characterized according to two axis: the set of modules in which the line can be decomposed, and the assembly plan. The performed analysis identified the following aspects:

- Though assembly plans are different, most of the operations within the modules are common in all assembly lines, such as riveting, welding, feeding, moving components and parts.
- The line motor is actually the same in all assembly lines, with minimal variations related to the specific motor transmitted power.
- The customized part of the line is represented mainly by the interfaces of the modules with the products and by the fixtures.

Hence, we can explore further the potentials of having circular MMS and its implications. Assembly systems producing complex products are normally very much dedicated to the specific product/component to be manufactured: therefore, capital goods are difficult to reuse. Therefore, having circular MMS especially for assembly systems requires novel engineering approaches in various aspects of MMS design and management. In particular, circularity shall introduce novel modular approaches to (i) assembly system design, which allows to reuse modules in different applications, and to (ii) pitstop manufacturing for fast configuration and ramp up of modular assembly systems. Then, monitoring of single modules (and not only complete machines) allows to continually assess the state of health of each module which is (re)used. Finally, module fleet management is needed to orchestrate the stock of modules during their lifetime.

3. Methodology

In this Section, the problem description is outlined. Indeed, the life-cycle management of manufacturing systems, and in particular of multi-stage automated assembly systems, in a Circular Economy perspective provides clear challenges towards sustainable development.

3.1. Life-cycle in traditional MMS

In Fig. 4, the logical sequence of phases for the concept, design, realization, use and disposal of a traditional MMS is shown, where continuous lines depict the logical sequence of phases and dashed lines depict the information flow. Each phase is assigned to the responsible actor in the MMS life-cycle, i.e. the MMS Customer, that is the manufacturer of assembled products needing the customized MMS, and the MMS Supplier, that is the machine tool builder (MTB). The peculiarity of multi-stage automated assembly systems is that they are characterized by short cycle time, thanks to the high level of automation and repeatability of operations, small

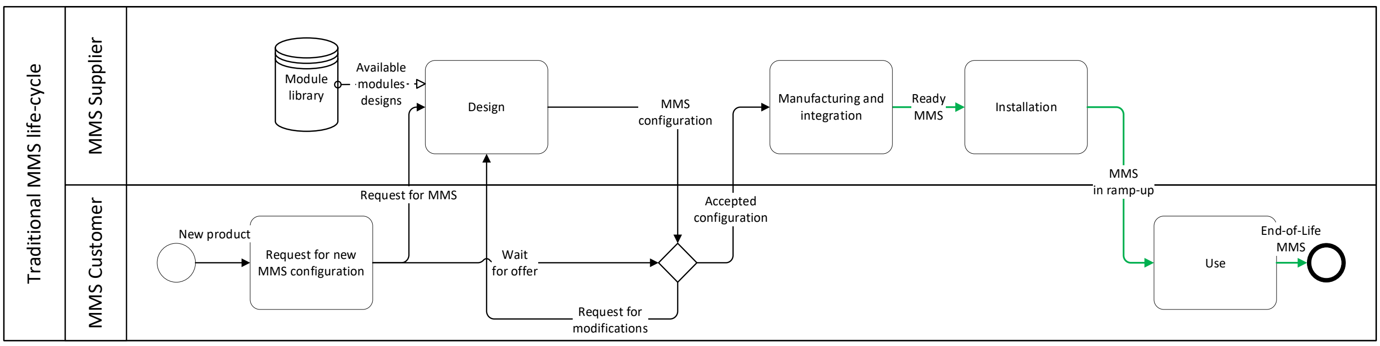


Figure 4. Sequence of activities according to actors in traditional MMS life-cycle.

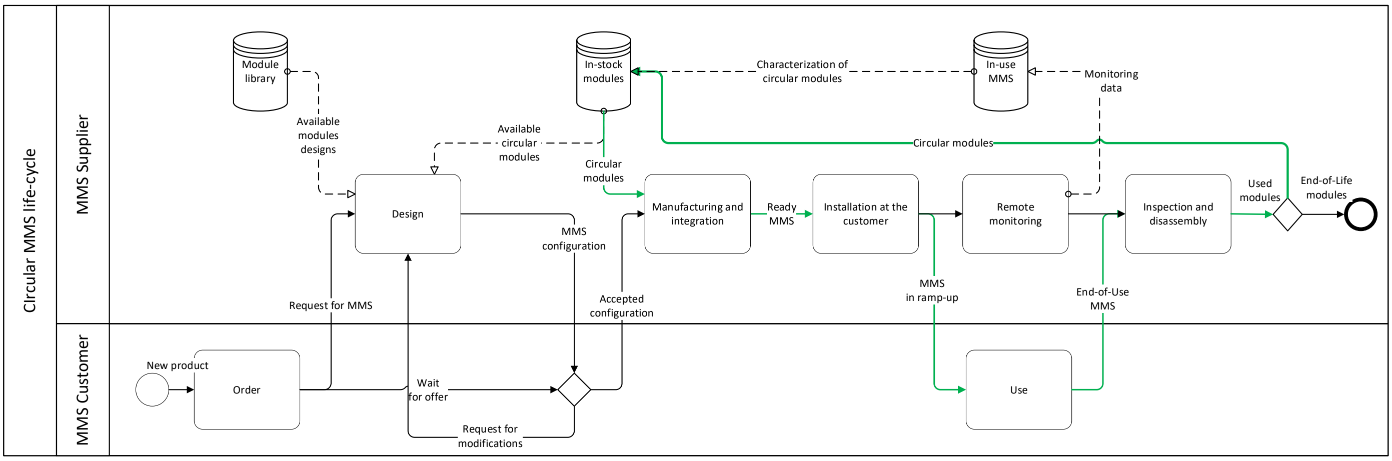


Figure 5. Sequence of activities according to actors in circular MMS life-cycle.

buffers for decoupling process modules may exist, stations are usually asynchronous and may work on batches. Product variants may be possible, following set-up of product interfaces of the modules. Moreover, they are usually highly customized on the product variants, which is why they require quite long design phases by the machine tool builder, following the customer specifications ('Request for new MMS configuration'). Hence, each multi-stage automated assembly system is specifically designed, built and installed for one customer only, in order to assemble a predefined set of product variants. Usually, the machine tool builder has a library of modules that may be integrated to design the manufacturing system configuration ('Design'). The modules may be own design of the system supplier, or be acquired from external suppliers. Once the configuration is approved by the customer, in terms of capabilities, capacity, and cost, the multi-stage manufacturing system is integrated, by acquiring and/or manufacturing the necessary modules ('Manufacturing and integration'). Then, it is installed at the customer premises for ramp-up and use phase ('Installation at the customer', and 'Use'). The life cycle of such systems depends on the product life-cycle. In traditional manufacturing business models, of multi-stage manufacturing systems (MMS), the customer of the MMS supplier, i.e. the MMS user, is responsible for the end-of-life of the MMS. Usually, these type of manufacturing systems are disposed, given the high level of customization. This can be noted in the graph in Fig. 4 where the green arrows depict the physical flow of the MMS, hence showing a linear life-cycle. In recent years, customers have pushed towards reconfiguration, in order to decrease the high investment costs in new production capacity, due to the frequent product changes. However, this would mean for the MMS user to acquire expertise in system design and configuration to take suitable decisions.

3.2. Life-cycle in circular MMS

Circularity enhances sustainability in the life-cycle management of assembly/disassembly systems, by disrupting the way these assets are designed, configured and operated. In particular, modularity at hardware and software level becomes a key technological pillar in future highly automated assembly/disassembly systems for short-run on-demand production campaigns. In this context, fast process planning supports the capability of an equipment provider to rapidly configure new assembly/disassembly systems by maximizing the re-use of existing modules, with a plug-and-play logic, still guaranteeing advanced technological solutions and performance. Therefore, the technology providers will change their business model, focusing on sustainable strategic innovation and fleet module design and management. If the machine tool builder uses a business model based on servitization, with the aim of managing the MMS as a circular product, we can distinguish a different set of activities with respect to traditional MMS management. The schematical activity flow is depicted in Fig. 5. As it can be noticed, not only the logical sequence of activities is changed, but also the responsible actors for given activities. For instance, the responsible for the end-of-life management of the MMS is not the user but the supplier. As a consequence, the MMS supplier, i.e. the machine tool builder, is highly interested in exploiting multiple lives of the MMS. This strategy hence requires additional technological actions, such as disassembly of the MMS, inspection of the modules, and decision on the modules about whether to keep them, by storing them in a warehouse, or dispose them. As a consequence, the machine tool builder becomes not only a designer of MMS, but also a manager of physical assets. This may become a constraint for the design and development activity, as the machine tool builder will aim at re-using as much as possible the available physical modules it has instead of designing and building new ones. From the information flow perspective, this is a massive change, as it will be discussed in the next Section. At a first glimpse, it is evident that the physical flow of MMS is now circular, as green lines highlight, and not linear anymore.

3.3. Information model for process-system level

In traditional MMS management, the MMS supplier has to manage information and data about the customer's order, and information about the modules, usually managed in a PLM software, here indicated as Module Library. The more the

Module Library is structured, and it contains structured data about the modules, as operations according to the type, capabilities, nominal characteristics, CAD models etc, the easier the configuration phase it is. Ideally, the configured system, i.e. the MMS, customized for the customer, is tracked and linked to the modules included in it.

When MMS are managed in a circular way, however, additional information should be managed, as in Fig. 6.

At system level, data about the in-use MMS are needed. This information can be gathered by means of remote monitoring, enabled by Industrial IoT. As the MMS supplier will take back the MMS at the end of the life with the current customer, it is extremely interested in constantly knowing the status, and the use condition, especially if the MMS supplier is also responsible for the maintenance, as it usually occurs in servitization business models. The advantage of gathering monitoring data is that, with respect to traditional MMS life-cycles, the machine tool builder can acquire direct knowledge about the dynamics and performance of modules included in the MMS, and that can be used for deriving more accurate models about the modules.

Hence, at process level, the machine tool builder has to manage information about the single modules: on one hand, perishability and obsolescence may become an issue, since the machine tool builder has now to manage physical assets; on the other hand, data from in-use MMS can characterize better the original module models.

As a consequence, the information flow becomes intricate and circular flows are necessary as well, to keep track of the multiple lives of the modules enabled by the circular MMS management.

3.4. Implications for the machine tool builder

The implications for the machine tool builder (MTB), as a consequence of the implementation of a pay-per-use business model, include new tasks in the company operations. If these tasks are not carefully considered and managed, Circular Economy of manufacturing systems may be hindered.

In particular, the machine tool builder has the following novel capabilities to develop within the company business functions:

- Design & Engineering: this function will be pushed to design modules and machines highly reliable and with longer life-cycles, as well as strongly standardized, and easily maintainable. Moreover, obsolete and unefficient components and modules should be avoided, calling for constant tracking of installed modules performance and feedback from the customer service to the design for improvement purposes and constant upgrades. Finally, the D&E should focus on providing fast and optimal configuration alternatives to new customers, considering the current module availability and the requested target performance. This activity is completely different from those which are characteristics of this function, hence new tools for robust system configuration design should be developed.
- Production logistics: production will integrate manufacturing and re-manufacturing activities. Hence, production logistics should focus on complex production planning decisions concerning the selection of reusable modules from the warehouse. Indeed, safety

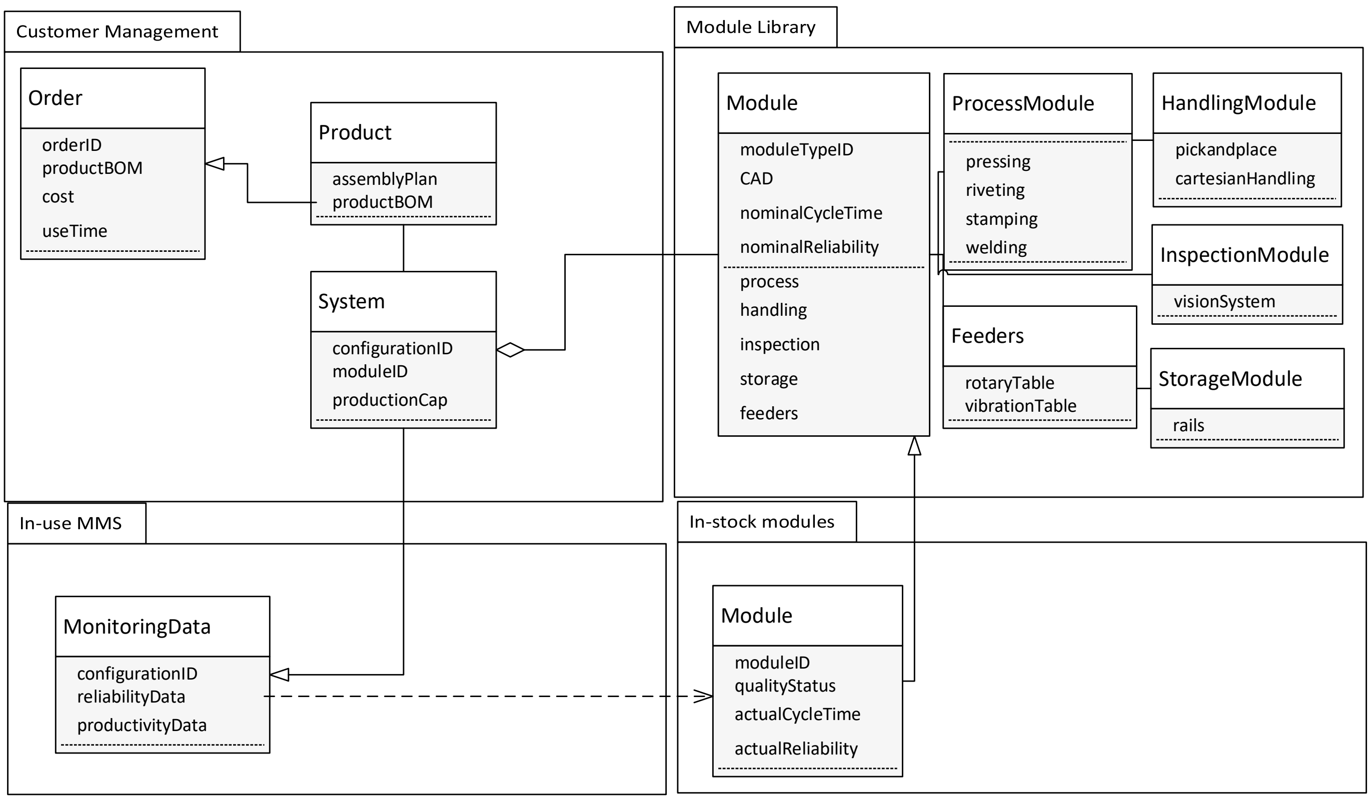


Figure 6. Information process-system relational model for circular MMS.

stock modules should be managed by bundling uncertainties and limiting the amount of unused capacity. Considering the new remanufacturing activities, novel incoming quality control stations must be configured, where the state of the systems after their usage is assessed and modules are disassembled for circular purposes.
- Customer service: this function should be enlarged and, as usual in servitization business, will represent one of the main cost center. Indeed, customer service will include constant remote monitoring of the installed systems to enable proactive maintenance interventions at the customer premises. Moreover, customer service is the main responsible for managing the installed system and keeping it in line with real needs, as well as managing the continuous improvement of the installed systems to enable constant updates and low obsolescence.

4. Open challenges and research directions

In relation to traditional business models and MTB companies, new challenges with respect to manufacturing systems design and operations arise, representing also clear research directions. In particular, the following objectives should be achieved:
- Fast ramp-up of new system configurations.
- Quick assembly and disassembly of modules.
- Effective remote monitoring of system performance.
- Easy maintenance and repair of modules and system in general.
- Easy upgrade of the modules.

However, manufacturing companies are not there yet.

From the hardware point of view, system architecture may need to be completely rethought, in order to apply traditional reconfiguration principles, including (i) modularity of the machine (interfaces - mechanical, air pressure, electrical, control); (ii) autonomy of the modules (the functions performed by a module are not affected by the other modules); (iii) universality of the modules (the same module can be used in different applications); (iv) simple performance analysis of the worn modules; (v) simple assembly/disassembly of the modules.

From the software point of view, new software applications may be required: (i) digital twins of the modules; (ii) digital twin of the installed systems; (iii) remote condition based maintenance of the modules; (iv) system design and fast quotation; (v) support software tools for manual module disassembly and reassembly; (vi) robust scheduling of the usage of the modules in different premises; (vii) planning the evolution of the stock of modules (quantities and types); (viii) financial planning considering revenues and investments in modules.

5. Conclusion

This work has presented the preliminary idea of the novel pay-per-use business model aiming at the Circular Economy of manufacturing systems. The application of such business model has been discussed in particular with respect to multi-stage automated assembly systems, as shown also within the industrial case study.

The novel business model definitely provides a step towards the sustainable development of manufacturing systems. Indeed, companies which are able to embrace this paradigm may outperform other players and remain sustainably competitive. Moreover, the overall benefit goes not only to companies, but also to the society, and may reduce the environmental impact by reducing the use of resources.

However, systemic changes in how usual business of machine tool builders is performed are required. Hence, multiple research guidelines have been provided to show the direction toward the successful implementation of sustainable development in manufacturing systems.

Acknowledgements

The Authors thank Mr. Gianluigi Viscardi, Mr. Mauro Viscardi and Cosberg company for the useful insights to the paper development.

This work was funded by European Commission within the Horizon Europe project RaRe2 (GA 101092073)

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