Product BOMs in different lifecycle contexts managed by a PLM system as a requirement for implementing digital twins

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Abstract: This work is based on a real case of digital twin implementation in one of the largest global mining companies; this firm was aiming to improve maintenance planning and management. The object studied is a subsystem of a car dumper, a critical piece of equipment in mining. This work concludes that without digital product bills of materials (BOMs) managed by a product lifecycle management (PLM) system, it is not possible to institutionalise the digital twin in a company; it illustrates a practical application of PLM system integration into computer-aided design (CAD) software. The BOMs are a requirement for implementing digital twins and provide the basis for the connection between the real and virtual worlds; they are the coalescent product structure for information registration and exchange. This work demonstrates that representative data related to digital product BOMs managed by a PLM system are the foundation for improving maintenance management in mining companies and that BOMs are a requirement for implementing digital twins.

Keywords: digital twin; maintenance planning; operational assets; bills of material; BOM; PLM system; software integration; CAD software.

Reference to this paper should be made as follows: Vieira, D., Schmoller, E. and Bravo, A. (2022) 'Product BOMs in different lifecycle contexts managed by a PLM system as a requirement for implementing digital twins', *Int. J. Product Lifecycle Management*, Vol. 14, No. 1, pp.1–17.

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1 Introduction

The digital twin aims to design and develop a product in the virtual environment under consideration of the best scenarios for its manufacturing and operation, while aspiring to monitor and gather data from the real product once it is being manufactured or in operation.

The definition of digital twins, considered as the basis of this research, indicates that the overall goal of the digital twin concept is to be able to closely follow the physical product during manufacturing and operation and simulate the process to launch the product in the real world based on the results of these simulations (Moyne et al., 2020).

Digital twins are defined as representations of components, assets, and processes to predict and optimise performance in order to achieve improved business outcomes (Gehrmann and Gunnarsson, 2019). The digital twin is a virtual representation of an entity in the real world (Piroumian, 2021).

Based on these digital twin definitions, there are emerging software programs to sustain the digital twin approach embedded in the digitalisation initiative, which virtualises business processes and product information. When virtualising product information, there are two worlds to be correlated: virtual and real. These two worlds at certain moments are integrated to exchange information. The virtual information is considered as the planned information in the digital environment, and it is compared and monitored for adaptation according to the performance of the product in the real world.

To avoid costs and reduce time to develop, manufacture and, mainly, reach the market, the product is designed and simulated in the virtual world, which generates virtual information. While the product is being manufactured or in operation, other information is generated, real-world information, while the earlier virtual information is also monitored to provide analytics based on the planned product.

The digital twin merges these two worlds, and this work aims to demonstrate that the link between them is the digital product bills of materials (BOMs) by using analysis and evidence related to a real case aiming to implement the digital twin, despite the lack of evidence in the literature that the BOM is the core of digital twin implementation. Digital product BOMs must be structured, managed and coordinated to allow the physical information from the real product to be correlated with the virtual product to leverage the product development and manufacturing planning for the next product.

Product BOMs must be established, connected and synchronised in different contexts throughout the product lifecycle to store information based on its content, not under the electronic document management (EDM) initiative but within the digital twin initiative.

The product lifecycle management (PLM) system offers a solution to structuring, managing and coordinating digital product BOMs in the different correct contexts, and it therefore represents the basis for institutionalising the digital twin.

This work aims to present a real case of a project institutionalising the digital twin approach in one of the largest global mining companies. The lack of digital BOMs managed by a PLM system was identified as a limitation when proceeding with the digital twin implementation, therefore representing a requirement for implementing digital twins. The study object presented is a subsystem of a car dumper. The subsystem lifecycle was considered from the design using computer-aided design (CAD) software integrated into a PLM system and continued until the maintenance planning using the PLM system functionalities related to the BOMs. The car dumper is a critical product involved in mining companies. All the ore that arrives at a port is unloaded by car dumpers, and this robust piece of equipment (weighing over 800 tons) is commonly capable of unloading two train wagons simultaneously. They are very efficient; an average unloading time for 136 wagons is approximately three hours to complete, and the nominal unloading capacity is 8,800 tons per hour. Problems with car dumpers can affect the company's entire logistics chain.

2 The application of digital BOMs in the industry and state-of-the-art

2.1 The different BOMs

The product BOMs describe the different structures of the different contexts for products, but product traceability, management, collaboration and control must be possible throughout the lifecycle, connecting all BOMs.

The digital twin is a key enabler of digital transformation, according to Kritzinger et al. (2018). A product cannot be managed in the virtual world unless its structures have been virtualised.

The uniqueness of the digital twin lies in its centralising the register of information into a core digital model of the product instead of obtaining information dispersed in different records and in different software that is commonly not integrated, and this centralisation must be established to allow an effective automatic exchange of information between the physical objects and digital objects (Tchana et al., 2019). There are too many data points to be generated and gathered along the product lifecycle in the digital twin initiative; in these cases, when there are too many software programs engaged in the data relations, it could imply too many possibilities to ensure digital twin data quality.

Along the lifecycle, the product will have different information scenarios; proper relations and management of this information are the success factors for implementing a digital twin. Figure 1 shows the different BOMs from the MCAD (mechanical CAD) structure and how the BOMs are related to the physical product.

The engineering BOM (eBOM) represents the product structure as designed; based on the industry segment, the MCAD and electronic CAD (ECAD) compose the eBOM.

Once the eBOM is defined, the manufacturing BOM (mBOM) must structure the eBOM items into raw materials to be manufactured; this is preceded by a bill of processes (BOP), which organises the steps of the processes related to raw material manufacturing.

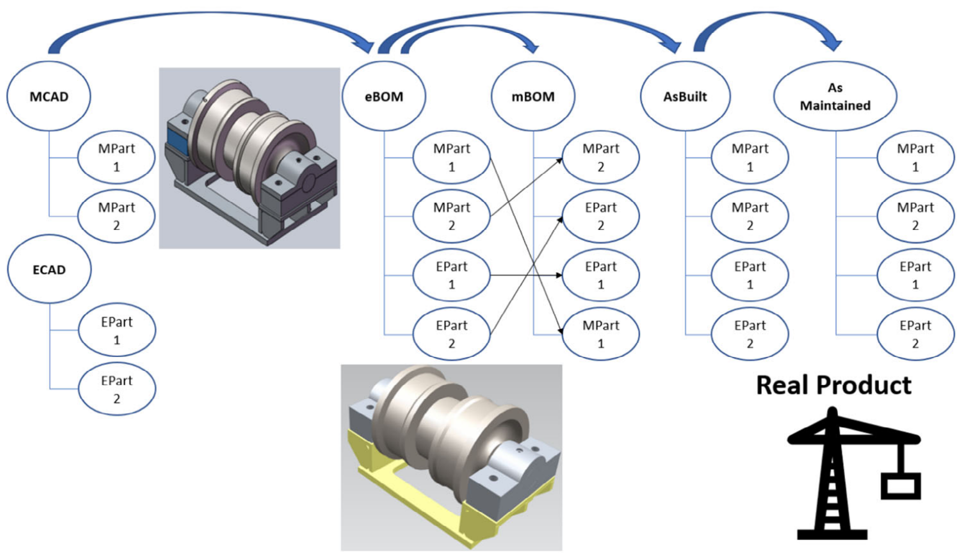
To be able to implement a digital twin, Haag and Anderl (2018) note that a unique instantiation from the universal model needs to be automated. The digital twin in the virtual world must be represented by the different product BOMs connected and synchronised along the product lifecycle. There are mathematical and geometrical models for simulating the product and for collecting manufacturing data, but this information must connect the virtual and physical world. This work proposes to demonstrate the possibilities of a PLM system for managing digital product BOMs through a real case example.

There is no common definition of a digital twin, mostly due to the variety of areas within different disciplines involved with the digital twin concept (Kritzinger et al., 2018). These disciplines have different interests in product information, which means different product BOMs.

From the MCAD to the as-maintained BOM, there is a virtual scenario; then, the physical BOMs, still virtualised, are the basis for simulations and used to attribute information related to the physical application of the product to the eBOM, but without losing the original structure and the as-designed principles. The as-built BOM, would assign the serial number to the eBOM items, for example. In the end, regardless of the serial number information related to the eBOM items, the as-maintained BOM must gather the real information, as the product has been used by customers or services, to identify gaps between the product as designed and as planned in the virtual environment and the product in real life. This latter BOM will gather information to report analytics and consider subsequent developments, as well as to manage product support in the market such as maintenance and spare parts, for example.

Figure 1 illustrates the different BOMs and their relations applied in the PLM system through its functionality modules considered in the scenario presented in this work. The CAD assembly (Figure 1 upper left) is designed as geometrical parts using the software Solid Works. Then, this MBOM becomes an eBOM in the PLM software Teamcenter, and the CAD assembly is represented by the international standard for 3D visualisation. JT, the published data format developed by Siemens Digital Industries Software (Figure 1 bottom middle). The assembly originating as an MCAD using the CAD software becomes a structure in the PLM software, and the JT files associated with the items in the eBOM provide references for manufacturing visual simulations. According to the physical parameters, weight and material provide a reference for physical simulations in the product development processes. Although this work does not consider an ECAD or an mBOM application, they are illustrated in Figure 1 to provide a sense of the connections in the product path through the BOMs. The mBOM is not considered in this case; the company considered this real case obtained the entire product from third-party manufacturers. The target is to correlate the MCAD to the as-maintained BOM to plan for the maintenance of the product (Figure 1 bottom right) and gather real information for the virtual world while the maintenance is being executed.

Figure 1 Different product BOMs (see online version for colours)



2.2 *The digital BOMs of the product*

The product structure comprises BOMs, and these BOMs must be managed in different contexts to represent the digitalisation of the real product and allow the exchange of virtual and physical information along the product lifecycle. The company mentioned in this work did not manage BOMs in the engineering and maintenance context, but only based on the MCAD generated by the CAD software. The product information was then manually input into the enterprise resource planning (ERP) system, making materials reuse and versioning a complex issue.

The key characteristics for developing a digital twin for a specific use case were identified by Shao and Helu (2020); one of the three key factors they describe is the context, which determines how information should be provided by the digital twin. The digital twin implements a bidirectional exchange of information between virtual and real worlds in the different phases of the product lifecycle.

Companies are resisting implementation of digital twins due to concern about the announced benefits related to reporting products analytics in the real world. However, the foundation for gathering and managing these analytics is the virtual world, and digital BOMs must be implemented to allow digital twin implementation.

Digital BOMs must be implemented using software to represent the different BOMs in the virtual world. However, studies are unfamiliar with the key technologies and tools for digital twins, and the selection of tools requires participants in academia and industry (Qi et al., 2019).

Jones et al. (2020) identified gaps for digital twin research, which comprise use cases and technical implementations. The aim of this work is to present a real case of a product being generated from the CAD software, to becoming an eBOM, and then an as-maintained BOM.

3 The challenges in implementing the digital twin

3.1 Differences in BOMs in different contexts of the product lifecycle

A digital twin is defined by Trauer et al. (2020) as a virtual representation of a physical system, and they are connected via bidirectional exchange over the entire lifecycle. The differences in product BOMs imply different information related to the product at different moments of the product lifecycle. If digital product BOMs are not implemented, the digital twin approach will not be possible, as the information will not have a specific address to be stored and considered for the reports and analysis.

Smart manufacturing has been individually researched in academia and industry, and Ren et al. (2019) concluded that the majority of industries are not well setup for smart manufacturing implementation, as smart product development is lacking. Specifically, this refers to data generation and collaboration among different disciplines along the product development phases until reaching the manufacturing phases and then, in production, relating the virtual data to the real data.

Digital twins are far from realising their potential because a variety of data types must be generated, collected and merged (Qi et al., 2019). The merging of virtual and real data through a digital twin must consider not only manufacturing data but also development data, since the product cradle is usually represented using of CAD software.

The CAD, text editor and spreadsheet editor software are commodities; commonly, companies use them as tools to structure the product BOMs, but these tools do not enable the company to manage the BOMs in different contexts. Often, these documents are duplicated or information is added to the same document along the entire product lifecycle, and so the product structure is not clear to the different stakeholders or manageable along the lifecycle.

Having all product, historical and real-time data in a single system is strongly required, according to Gehrke et al. (2020). The PLM system provides the capabilities needed to be implemented as the backbone for digital twin solution implementation, but even before considering digital twin implementation, the PLM system concept and adoption of its functionality must be considered.

Structuring the data and enabling its use across the asset lifecycle is a major challenge (Erkoyuncu et al., 2020). There are usually too many software programs integrated in the effort of implementing a digital twin, and many companies are using an approach that starts from manufacturing and ends in development. However, real data must be synchronised to the virtual data to allow the product evolution for the next version lifecycle.

One of the Industry 4.0 implementation possibilities is the product lifecycle, which is mentioned by Arm et al. (2018). The fourth industrial revolution is based on PLM for establishing cyber-physical connections; this includes understanding the previous product lifecycle through virtual and real data comparisons to make better decisions regarding the new product lifecycle. The digital twin is one of the pillars for managing the product lifecycle.

Effective lifecycle management with the digital twin must consider all phases of the project (Tchana et al., 2019). In addition to product development, the project control monitors progress through the lifecycle and gathers information from the different contexts of the product, represented by BOMs, while the product lifecycle evolves.

There is a lack of real cases of the application of PLM systems in digital twin implementation. This work aims to contribute to this issue by establishing the usage of a PLM system for managing product BOMs as a requirement to implementing digital twins. This requirement results from the need to manage different product BOMs in the engineering and maintenance contexts; until this need was addressed in the PLM system, the digital twin implementation was blocked.

3.2 Relation between virtual and physical information

Tao et al. (2018b) published the state of the art regarding digital twins in industry and concluded that one of the most pressing issues to making digital twins viable in practice is a unified digital twin modelling method, which is critically needed. Digital models comprise numerical models for simulation and data analytics, but a single model to structure the product in the virtual world must be considered. The PLM system provides these capabilities. Ferguson et al. (2017) applied a numerical simulation using the STAR-CCM+ software to enhance the ability to digitally simulate a product.

Digital twin technology is the key technology for realising the fusion of physical and virtual models, as reinforced by Zheng et al. (2019). This work aims to demonstrate that digital BOMs are the key to realising digital twin technology, using the application of a PLM system as the basis for relating virtual and real information once the system has structured the product BOMs.

One of the main benefits provided by digital twins is that they mirror the manufacturing and maintenance processes (Schützer et al., 2019).

A lack of approaches for adaptation is one of the main issues preventing industrial adoptions of digital twins (Erkoyuncu et al., 2020). Product digital BOM integration and adoption could leverage digital twin adoption.

Often, there exists a gap between the models and real-life physical products (Lupinetti et al., 2019). According to Schützer et al. (2019), to fully harvest digital twins' potential, virtual twins must be combined with resources in the real world.

According to Tao et al. (2018a), the volume of data collected in manufacturing is growing.

The integration of physical and digital worlds is the key for smart manufacturing, but most studies focus on data from the physical world instead of data from virtual models (Tao et al., 2018a).

Virtual and physical product attribute transmission is discussed by Qi et al. (2018), who mention that physical parameters are transmitted to virtual models and then fed back to optimise physical entities.

Much effort must be invested in determining how to connect PLM systems and devices, according to Boschert et al. (2018).

A literature review of the relation between virtual and physical information demonstrates that the use of PLM software to manage digital product BOMs to correlate the virtual and physical worlds has not been explored.

4 PLM system to structure, manage and coordinate digital twin information

This article is limited to discussing the application of PLM systems to structure digital product BOMs for the purpose of this work. The PLM system is composed of modules, and through functionalities, it is possible to structure a product in many different contexts. Once the product information becomes data in the system, they can be linked and managed in an integrated approach.

In the context of digitalisation, the capture, storage and analysis of data is essential, as reinforced by Uhlemann et al. (2017).

There are some research challenges in implementing digital twins:

1 the digital twin comprises multiple models of varying granularity that describe various aspects across the lifecycle

2 the models need to be interlinked and synchronised with the asset (Erkoyuncu et al., 2020).

These challenges can be addressed by the PLM system starting with the initial product development using CAD software.

PLM systems handle many more types of data than geometric data alone (Lupinetti et al., 2019). 3D CAD models are the central representation used to convey information (Lupinetti et al., 2019), and as Tchana et al. (2019) observe, the 3D model is no longer a digital model but the digital duplicate of the product.

According to Gehrke et al. (2020), the users of PLM systems should learn the system in practice and then define their specific needs for functionality, which reinforces the need for PLM system adoption before investing in digital twin implementation.

A 'digital twin in manufacturing' literature review (Kritzinger et al., 2018) shows that the digital twin literature consists of concept papers without concrete case studies. This work presents a real-world case.

It is difficult to implement assemblies 4.0 before seeing it in practice, as mentioned by Fast-Berglund et al. (2019). They also comment on the need to import legacy data when implementing this approach.

Before implementing the digital twin, once the PLM system is implemented, data must usually be migrated to include the previous product data in the system. If it is to be used as the basis for developing and manufacturing the next product, the companies looking to adopt the digital twin must sanitise and prepare the data for digital twin technology adoption; failure to do so can prevent the adoption of this solution.

The implementation of an ERP system to support the tasks of an industrial enterprise allows the firm to increase the manoeuvrability of its actions in response to change, according to the work of Syreyshchikova et al. (2020). The PLM system also works by leveraging and enabling PLM through the digital twin. Because of the increase in ERP implementation and its adoption before PLM software, companies usually connect CAD information to ERP information; this approach lacks the ability to consider intermediate information and analysis in a managed environment.

The digital twin supports capability development for smart products but still requires research (Tomiyama et al., 2019). This work contributes by examining the application of a PLM system to manage digital product BOMs, which can be considered a digital approach to developing products.

Industry 4.0 concepts suggest the use of a PLM system that cooperates with ERPs and manufacturing execution systems (MESs), according to Arm et al. (2018). The PLM system works as the backbone for the product lifecycle, with emphasis on the development and planning tasks, including simulations of the product and the production process. This system must be integrated with the other systems to exchange and coordinate information along all phases of the product lifecycle.

Current data collection technologies are not fully ready for smart data perception, particularly when there are different communication interfaces, as mentioned by Tao et al. (2018b). Bachelor et al. (2019) also note that proprietary languages, syntax and formats are issues affecting tool integration for digital twin implementation.

Even before the addressing challenges for gathering data to be analysed, there are issues in connecting systems to address the data and act on the results. PLM systems have the capability to be integrated into other systems through common protocols that allow the PLM to act as a data source for other systems and to receive their data.

The PLM system Teamcenter was used by Praeger et al. (2018) to develop a serial vehicle. They used the system module as-built Manager to create a unique serial number for each part, which was converted to a QR code to be printed on the part. They point out that the PLM system connects the serial and the part number, such that the correct connection ensures that all the documents and parts are well managed, including revision quality control.

Using the PLM system configuration presented by Praeger et al. (2018) allows us to obtain a part code from a physical part through a scanner, which automatically fills the search field in the system to obtain the virtual part.

Computer-aided technologies (CAx) models are not designed to live on as digital twins, according to Haag and Anderl (2018). These models are the basis for the product BOMs, which represent the virtual basis of digital twins.

Based on the limitation to implementing digital twins identified in the case considered in this work, the management of digital product BOMs in different contexts was considered as a prerequisite for implementing digital twins, and the PLM system functionality for BOM management fits that requirement.

5 Implementation of digital BOMs

The real case presented in this work considers a subsystem of a car dumper, as illustrated in Figure 1 (bottom right). Approximately 10,000 CAD files compose the MCAD of the car dumper. The complete car dumper eBOM is represented by the car dumper as the main asset. Below it, there is a structure initially composed of 11 main systems, including the civil construction infrastructure as elements of the car dumper. The subsystem considered in this work is a part of the complete car dumper, but the given considerations for this study object are the complete car dumper digital BOM implementation conducted in the case.

The subsystem illustrated in Figure 2 is first created as an MCAD (Figure 1), which is on the left side of the CAD software (A). Once the PLM system is integrated into the CAD software, the eBOM is structured on the right side (B); it is already in the CAD software, meaning the product design environment. Each component in the mechanical assembly is represented by an item that will be placed in an eBOM.

The CAD software allows us to assign a component reference to the components in an assembly (C) and to have the same component in different assemblies; that information must be stored in the PLM system and allocated to the eBOM attributes to allow further BOM structure. This initial scenario demonstrates the different contexts of information generation, and from the beginning, all this information must be integrated.

Figure 2 MCAD and eBOM integration between the PLM system and CAD software (see online version for colours)

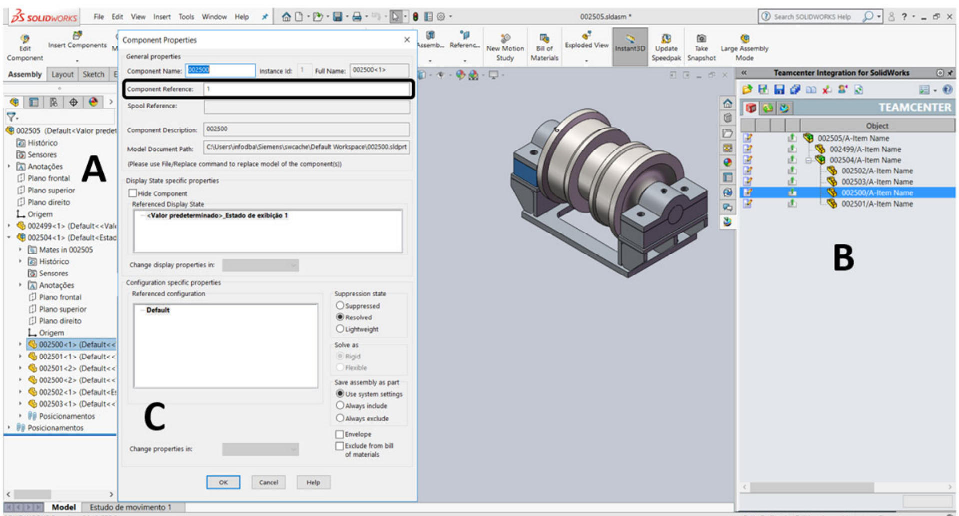
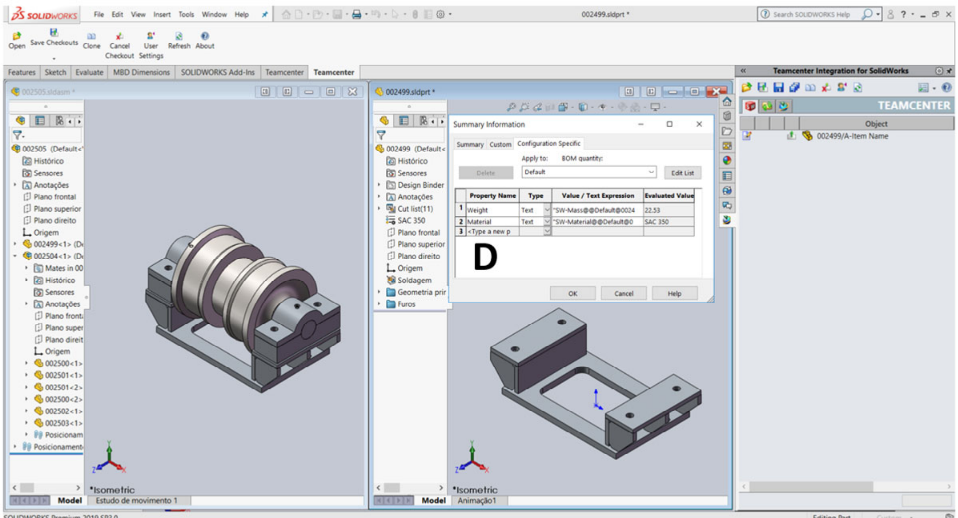


Figure 3 illustrates the information generated in the CAD software for one component of the subsystem: the material applied to the component and the weight of the component according to the material applied (D). Both pieces of information are master recorded by the CAD software but also must compose the item in the PLM system. These physical attributes already given by the CAD software will be integrated into the PLM system, for example, for further manufacturing simulations. Additionally, each geometrical part will become a JT file in the PLM system (Figure 1 bottom middle).

Once the component is designed, aided by computer, the information generated in the CAD software will be automatically transferred to the item in the PLM system; the new information related to the designed component was previously input when the item was created. The items for the eBOM have a 'system subsystem component' property containing a list of values (LOV) to indicate if the component designed is a system, subsystem or component of the product structure. Another property, 'description' is an LOV related to the previous 'system subsystem component' that describes the component based on the declared type. While being created, the item can also be automatically applied to a workflow to automate the information collaboration straight from the CAD software through the PLM system integration interface starting with the geometrical part creation.

Figure 3 Attribute integration between MCAD and eBOM (see online version for colours)



The MCAD are represented in the PLM system as an eBOM, and the information generated in the CAD software is stored as item attributes; if there was an ECAD (Figure 1), it would also be placed as items in the eBOM. The eBOMs are represented as 3D graphics in the PLM system using a JT file generated from the geometrical part designed in the CAD software. New information is added to the eBOM items, and the items are represented by an identified and unique entity in the PLM system. The items can be worked with in different contexts using PLM system modules, which allows for the creation and management of other product BOMs, based always on the same item created from the CAx software.

The eBOM represents the base structure or origin of the as-maintained BOMs using the PLM system modules. From the eBOM, the as-maintained BOM was created to register and manage the information related to equipment operation in the real world. The as-built BOM was not considered in this work because a single car dumper was considered. If there are more car dumpers or even different equipment that includes shared components, the as-built BOM would be considered between the eBOM and the as-maintained BOM to control the positioning of the eBOM items for the equipment in the real world before managing the information on how the equipment has been maintained.

All the BOMs are based on the same item as initially created in the MCAD, allowing for different structures according to the product's context along its lifecycle. Once the as-maintained BOM is created, the maintenance plan is created based on the items, including the procedures and work orders needed to execute maintenance.

These BOMs manage the created virtual information and were able to receive the information from the real world to generate analytics based on the data storage in the PLM system.

The equipment is not physically controlled by hardware to gather information without a human interface, but the information gathered during actual equipment maintenance is registered using an interface available through a tablet in front of the equipment. The registered information is immediately correlated to the items in the BOMs, and the JT file generated from the geometrical parts is consumed for simulation animations and available to guide maintenance. If a component is sent to the garage for repairs, once the information is registered using the tablet interface, the item in the BOM corresponding to this real component is changed to incorporate the inputs from the real world.

Implemented BOMs through the PLM system functionality result from the company preparing to gather real data; then the scope of this work is limited to demonstrating the MCAD conversion to eBOM as the foundation for proceeding toward real and digital information correlation.

6 Considerations and discussion

This work presented the use of the PLM system Teamcenter to structure the different products in BOMs, since the CAD modelling of BOMs is related to the physical context in the real world. The PLM system provided many capabilities: capturing product data from the MCAD model in the eBOM; maintaining the link between the MCAD assembly and the as-maintained BOM items; storing the CAD models in the eBOM items; representing the 3D models in the PLM system while maintaining the relationship to the corresponding eBOM item; and attributing different information to the same items while offering different views of the product to generate information for the BOM corresponding to the product context.

When the digital product BOMs were structured, the real information could be addressed to the items to establish the correlation between the virtual and the physical worlds.

The integration between the MCAD and the eBOM was made possible by using the same item in different assemblies because the eBOM items could be placed in new assemblies; this new instance allowed us to input attributes related to the CAD model corresponding to the new assembly without affecting the use of this eBOM item in other assemblies. Additionally, the attributes inputted to the CAD model were reflected in the eBOM, including when the CAD model of other assemblies used the same eBOM item with different values.

The attribute of the 'system subsystem component' property contained an LOV that indicated if the designed component is a system, subsystem or a component in the product structure; this directs the PLM system to input and structure the data inside the BOMs according to the rules corresponding to item correlation and hierarchy.

The company's objective in implementing the digital twin was to improve the planning and maintenance management of the equipment discussed in this work and to collect real product information to continuously improve the process. However, the company faced some challenges, including conceptual issues regarding the types of BOMs, when implementing the PLM system, and questions emerged related to definitions for integrations between CAD software and the PLM system.

The company's process before the adoption of the PLM system was represented by the origin of the information in the CAD software, a PDM (product data management) system embedded in the CAD software, text editors, spreadsheets and then an ERP system used to manage the execution of maintenance. The company adopted an approach composed of three main steps to institutionalise the digital twin:

1 compose a database of 3D model assemblies to include the items and BOM origins and enable product visualisation in the virtual world

2 structure the BOMs through CAD software and PLM system integration

3 equip sensors for the equipment to automate the collection of real-world information. This work considered the two first steps.

Figure 4 illustrates the improved process based on BOM creation through the PLM system. The company as-is scenario considered the use of the CAD software embedded in its PDM system, after which there was no more connected information for maintenance planning and management and therefore no basis for correlating the virtual and real information to improve the planning process.

The company to-be scenario considers the CAD software integrated into the PLM system, with a bidirectional exchange of live information. The MCAD then becomes an eBOM in the PLM systems, the as-maintained BOM is created based on the eBOM, maintenance planning is performed based on the BOMs, and maintenance management is based on the virtual and real correlated information. The PLM system was not integrated into the ERP system in the presented case; this was planned for next project phase, once the BOM items could be correlated to the ERP items. However, the integration between the PLM system and the ERP in Figure 4 illustrates this possibility. In Figure 4, 'Integration1' represents the integration between the software CAD and the PLM system to transform the MCAD into the eBOM. Once the eBOM created in the PLM system manages the other BOM creation and management, all the integrations among the systems ensure synchronised information management and links. 'Integration2' represents the integration between the PLM system and interface developed for a tablet, where real-world information gathered during equipment maintenance is registered, and the registered information of the BOMs is accessed. 'Integration3' represents a possible integration between the PLM system and the ERP system to collaborate and correlate maintenance information related to planning and execution, which includes automated and integrated work orders created from the PLM system for the ERP system based on the BOMs. The PLM system is the backbone for the information exchange among the systems, and the BOMs are the core of the PLM system that correlate the virtual and real worlds.

The improvement references used to validate the to-be scenario are regularity in the process, speed in the process, agile searches, the reuse of information, control of the information, and coalescent digital product structures. The performance measurements are out of the scope of this work because the period of operation started after the implementation of the PLM system. This work represents the implementation of BOM management using a PLM system as the basis for relating real and virtual information, aiming to access virtual information while gathering information from the real world and then correlating both types of information. Subsequently, the company started to operate the process by using the to-be scenario (Figure 4).

Figure 5 illustrates the information from the integrations, which relate the virtual and real worlds. The pieces of information provided by integration 1 correspond to the MCAD parts transmitted to the items in the eBOM, and this information provided by the CAD software usually represents physical information related to the geometrical model.

The information 'component reference' (Figure 2) is very important information, which implies the reuse of an item from an eBOM and represents a part from the MCAD in multiple assemblies. Because this information is a particularity of the part in the assembly and is then transmitted to the item in the eBOM, it could be reused in different assemblies with no duplication of the item. The 'component reference' information could be filled out according to a company business rule to represent the reuse of an item in different products.

Figure 4 Role of the PLM system in real and virtual world information exchange (see online version for colours)

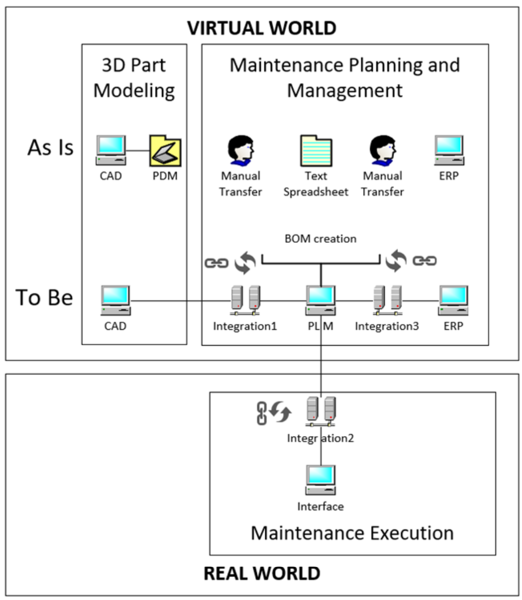
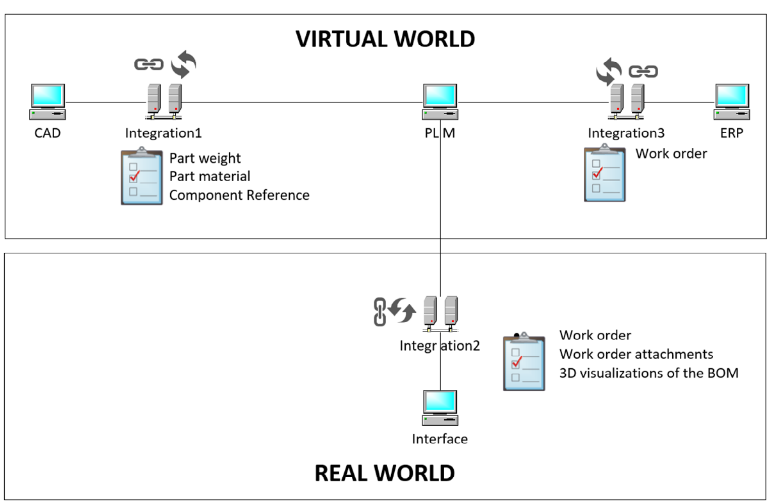


Figure 5 Information from the integrations (see online version for colours)



Once the eBOM evolves to the as-maintained BOM inside the PLM system, the pieces of information provided by integration 2, especially the work order, are related to the items in the as-maintained BOM for performing the equipment maintenance. In addition, it is also possible to register information gathered during the maintenance execution as attachments of the work order and to access 3D visualisations of the items of the BOM.

In regard to the information provided by integration 3, in this case, the work order is related to the items in the as-maintained BOM, and the information gathered from integration 2 is further related to the original work orders.

A single case study was considered in this work because of the current lack of access to practical approaches and cases, as identified through a literature review. Then, based on the types of potential single case projects presented by Yin (2015), the digital twin initiative performed in the company represented a valuable possibility for analysing practical issues regarding the relation between real and virtual information. This real-world case indicates that without digital product BOMs, a company cannot institutionalise the digital twin approach because without registering the information in BOMs, the pieces of information would not provide a cohesive and coherent holistic purpose of the digital twin, which proposes the connection of information related to the product that comes from the real and virtual worlds. Therefore, if the information related to the product was not addressed to the items in the BOMs, it would not be possible to move forward with the aim of gathering information from the real world and correlating it to the information in the virtual world. Consequently, further digital twin gains are possible due to the use of BOM management as the basis for integrating the PLM and ERP systems, for example, in component purchase planning. This approach ensures consistency in company operations, reinforces the added value in the operations through consistency of information registering, maintains consistency in the volume of ore transport based on the proper information managed by the integrated systems and prepares a database to improve the management of equipment maintenance.

7 Conclusions

The aim of this work was to show that digital product BOMs in a PLM system are the basis for relating real and virtual information in the digital twin context through the real case of a global mining company looking to improve the maintenance planning and management of a car dumper, a type of robust and critical equipment used to unload wagons with a nominal unloading capacity of 8,800 tons per hour.

A literature review showed that a correlation between virtual and real information is provided by digital twin technologies, but there is a lack of practical approaches and real cases, including a lack of individual research on digital twins in academia and industry.

Based on a subsystem of a car dumper as the object of study, the progress of the digital product BOMs from the MCAD to the as-maintained BOM was presented in this work as the core of digital twin implementation in this real case, which aims to correlate real and virtual information to improve maintenance planning and management of the product. In addition, the correlations between the MCAD and the eBOM were presented through the integration of CAD software and a PLM system.

The PLM system was considered the backbone for digital twin implementation in the company, and without digital product BOMs, it would not be possible to institutionalise the digital twin approach because the correlation between the real and virtual information was based on the BOM items represented by the information registered in the PLM system.

This work considers a single case study because there is a lack of access to practical and real cases that are available for analysing and gathering detailed information, which reflects the issues for implementing the digital twin. Based on this real case of a global mining company, it was found that the BOMs represent the core of the digital twin concept and provide the basis for the connection between the real and virtual worlds because they represent the coalescent product structure for information registering and exchange, which are addressed to the items in the BOMs, managed by a PLM system. Without implementing the BOMs in the PLM system to correlate the information between the real and virtual worlds, the company's purpose of seeking improved maintenance planning and management through the digital twin initiative would not have made progress to be deployed.

The mean time between failures (MTBFs) based on the use of digital BOMs in the digital twin context and improvements related to the management of spare parts for an asset in the mining industry based on more representative data related to the BOMs were identified as future gains based on the contribution of this work.

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