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Supporting the digital thread through the principles of complementarity

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Abstract

To establish a coherent Digital Thread, encompassing diverse information obtained during the design process, it is imperative to ensure the traceability of information particularly between engineering and manufacturing teams. A challenge lies in maintaining links between data, particularly in the context of configuration management. Through the principles of complementarity, we explore links between the Engineering and the Manufacturing definitions through a major structural element. We forsee the principles of complementarity as a support for Digital Thread throughout the product lifecycle.

Keywords: *digital thread, complementarity, configuration management, design structure matrix (DSM), bill of materials*

1. Introduction

1.1. Digital thread and configuration management

Specialists from diverse disciplines and industrial sectors, including the supply chain, must harness a wide array of information types. This necessity drives our pursuit of a seamless Digital Thread.

The Digital Thread could be defined as an approach to link and orchestrate all the data through the whole life cycle of the product from engineering to manufacturing and service (Kwona, 2020). Hedberg et al. (2020) highlight the importance of linking heterogeneous lifecycle data, that includes geometry, tolerances, manufacturing plans, manufacturing processes, bill of materials and many other elements to maintain information coherency and traceability in digital thread. To address this aspect, a most common approach is the master model, acting as a source of truth (Hoffman and Joan-Arinyo, 1998). This model aims to ensure data coherency to support configuration management through a centralised data model Solid modelling techniques are often utilised in its creation and maintenance. This approach could be applied for part manufacturing where the solid model efficiently guides the design of the numerical tool paths for Computer Numerical Control machining. However, the master model approach proves less suitable for complex products necessitating large-scale mock-ups of various types, supported by multiple Bill of Materials (BOMs). One critical aspect of maintaining a coherent Digital Thread is the seamless exchange of information ensuring data consistency across the design and manufacturing lifecycle to facilitate collaboration and effective configuration management. The BOM, serving as a product data structure representing a specific domain, streamlines the process of defining and retrieving product data. In turn, a set of BOMs offer complementary information about the relevant stakeholder's area of expertise and the product life cycle development.

The integration of engineering and manufacturing is facilitated through the Engineering Bill of Material (EBOM) and the Manufacturing Bill of Material (MBOM). The EBOM represents essentially the spatial definition of the product, while the MBOM represents the manufacturing process and assembly sequences. By establishing proper trace links between the EBOM and the MBOM, these domains can synergize to form complementary data structures. This interaction empowers manufacturing engineers to properly define the manufacturing process and collaborate seamlessly with the product definition team. This process should enable robust control over any changes, revisions and modifications related to the product, ensuring stringent configuration control and preserving the integrity of the Digital Thread between engineering and manufacturing domains. To ensure the data structures coherency this process should be semi-automated, and it becomes evident that effective configuration management requires not only change tracking through a proper set of relationships.

1.2. Complementarity principles

In the context of product design and manufacturing, the original concept of complementarity has evolved from different perspectives, such as economical, organizational, etc. From the point of view of economic theory, the factors of production (labour, capital, land and entrepreneurship) are said to be complementary when they are jointly needed for production so that each is needed to create a product, and none of them are interchangeable as presented by Gladwin (Gladwin, 1979). Later in 1990, Milgrom and Roberts (Milgrom and John Roberts, 1990) introduced this notion, suggesting that firms may increase their production more than proportionally if they achieve complementarity between subsystems of the organization. Complementary data structures organise and manage product data across different domains to support various stages of the product life cycle. Integration between complementary data structures is essential for maintaining the alignment and the consistency across the product lifecycle. Interoperability between various systems and tools enables the synchronization of data, ensuring accuracy and efficiency in product development and manufacturing operations. The concept of complementarity was further developed with the formulation of complementary data structures for Manufacturing Process Management (MPM) in the research work presented by Gagné and Fortin (2007). In recent developments, The International Council on Systems Engineering (INCOSE) has formed a working group on Tool Integration and Model Lifecycle Management, that is dedicated to the need of having integrated tools and environments to enhance productivity and elevate the quality of systems engineering practices (INCOSE, 2014). Currently, the search for a complementary and federated approach to manage complex product development is therefore an important goal in Systems Engineering. This is also the current aim of the Open Services for Lifecycle Collaboration (OSLC, 2023) which proposes methods and vendor independent protocols, which allow interconnecting information distributed over different tools and respective data repositories (Elaasar and Neal, 2013). The OSLC is based on web standards for communication and definitions of ontologies. Tools implementing OSLC are expected to provide simple yet powerful means for the experts of different disciplines to establish links between elements of digital artifacts. These links allow for change notification, and hereby aim to facilitate seamless information flow in the Digital Thread. OSLC is currently being developed in an open format and the development of a full Digital Engineering and Manufacturing System is the main goal of the initiative based on federated systems which are supported by proper relationships such as those of the Engineering to Manufacturing interface.

With the growth of multidisciplinary products/systems and teams, the notion of complementarity to support federated systems becomes more and more important. We propose to describe the complementarity of two federated systems based on the following principles: the affinity of their functions and their irreducibility of their systems essence, combined with the definition of sophisticated relationships between systems entities (Brovar et al., 2021). At the functional level, two systems are considered affine if the purposes of their use are in the same functional domain and, thus, allow them to be interfaced and placed in close relationship. In turn, the irreducibility of systems can be considered as the impossibility of reducing one system into another without losing its essence, since each of them contains a different information structure which includes a different set of information. We define the concept of sophisticated relationships as a dynamic and modifiable set of

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links of various types to provide interrelated functions between the elements of the system ensuring a robust functionality which can maintain configuration control and ensure the continuous digital thread. It is important to note that such types of interfaces could be one-to-one, one-to-many and many-to-many relationships.

Our main research hypothesis is that the principles of complementarity apply for systems and products of all scales, from systems of systems to small subsystems and component interfaces, since it could be applied to the physical, process and organizational domains. We demonstrate their applicability in the current paper on a specific use case that has been fully tested in industrial practice. However, this approach can also be applicable across other domains within the product/system lifecycle

1.2.1. Complementarity of EBOM and MBOM

Gagné and Fortin (2007) present a powerful tool for design and manufacturing integration based on the concept of complementarity to formulate complementary data structures for Manufacturing Process Management (MPM) as shown in Figure 1. They demonstrated a complementary approach based on the compatible nature of the EBOM and of the MBOM. By the term compatible nature, we define here the affinity of the functional domains of engineering and manufacturing functions, that allows these systems to be integrated through various types of relationships.

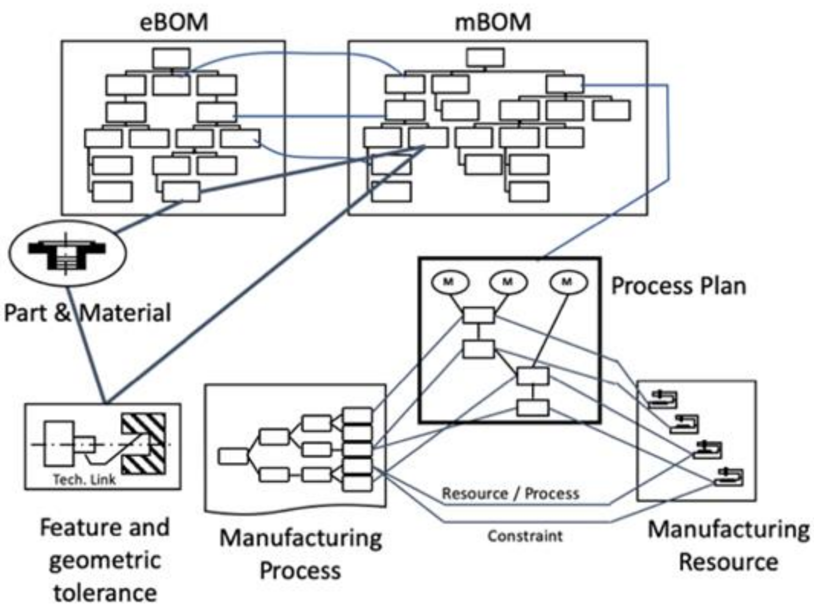

Figure 1. MPM data structure (Gagné and Fortin, 2007)

As an example, in Figure 1 above, the EBOM represents the structural decomposition of a product and, in essence, carries a spatial dimension at the detail design stage. In turn, the MBOM includes all components of the EBOM, since the complete product must be manufactured and assembled but with much more information such as tooling, stock and manufacturing processes and others, but is also structured very differently to represent the production process sequence as represented in Figure.1. Thus, it should be considered irreducible to the EBOM. In essence, irreducibility in systems suggests the impossibility of reducing one system to another without losing its essential characteristics. For example, in the aerospace domain, a combustion chamber in a jet engine is represented by a single part number in the engineering definition (EBOM). However, in manufacturing planning, where the MBOM is defined, it is represented by multiple parts that require welding through various manufacturing processes. Thus, on the one hand, the MBOM is compatible with the EBOM, but in fact it is irreducible, since it contains different and additional information with respect to the EBOM.

A similar approach has been fully developed, tested, and implemented in large scale manufacturing systems applications in several industrial domains. MPMLink, as part of Windchill (PTC., 2024), is an

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integrated solution for Product Lifecycle Management (PLM) that facilitates the seamless exchange of product data between engineering and manufacturing teams thus fostering collaboration. It has been shown to efficiently support the concurrent engineering process under tight configuration control and to integrate the product mock-up with Manufacturing Resource Planning (MRP) and Enterprise Resource Planning (ERP) to support the supply chain logistics.

1.3. DSM and MDM

To ensure smooth information synchronization between the EBOM and the MBOM for robust configuration management, it is crucial to establish effective mapping between these data structures. In this context the Design Structure Matrix (DSM) (Browning, 2001; Eppinger and Browning, 2012; Steward, 1981) can support interface management, which has already been proven to be effective as a tool to represent the model complexity in matrix format, ensuring the consistency in interfaces definitions and their management (Browning, 2001). The DSM is effectively a “network modeling tool used to represent the elements comprising a system and their interactions, thereby highlighting the system's architecture (or designed structure)” (Eppinger and Browning, 2012). Thus, a DSM has such capabilities that make it a universal approach to not only analyse the structure but also the system behavior through the demonstration of the interactions, which is extremely important to achieve a seamless integration of the system. It is not by coincidence that the DSM as a method itself, has been extended to Multi-Domain Matrix (MDM) (Maurer and Lindemann, 2008), which involves a structured framework for consistently defining, linking, and managing essential data across various domains, through the arrangement of multiple DSMs and the mappings between them.

1.4. Paper objectives and structure

The aim of this paper is to highlight and document the principles of complementarity between an EBOM and an MBOM that can enhance a strong digital thread. To illustrate this idea in Digital Engineering, we use a simple example involving an aircraft pylon front mount. We use a straightforward MDM-based approach to explain how the definitions of an EBOM and an MBOM can be linked to connect the engineering and manufacturing aspects. The MDM approach is considered the most appropriate for achieving interaction between the EBOM and the MBOM due to its inherent ability to represent and manage complex dependencies and relationships within a complex system structure. Furthermore, this tool allows for the modular representation of components and processes, providing a detailed depiction of dependencies and relationships. By capturing dependencies across different functional domains, MDMs enable seamless integration between engineering and manufacturing perspectives.
The paper has the following structure. Section 2 is dedicated to the overview of an Engine Front Mount case study, where we discuss a DSM-based representation of its EBOM (sub-section 2.1) and MBOM (sub-section 2.2). Section 3 is dedicated to the overview of EBOM and MBOM Integration (subsection 3.1) and configuration management support through the MDM-based approach (subsection 3.2). The Discussion and Conclusion will be in Section 4.

2. Front Mount Aircraft Engine case study

The case study is based on the Eagle Star Aviation student project, cooperating with 3 main partners including Bombardier Aerospace (BA), Pratt and Whitney Canada (PWC) and Bell Helicopter Textron Canada (BH). The project is related to the full engine retrofit, modifying the Pylon of a CRJ700 manufactured by Bombardier. The aircraft pylon plays a pivotal role in aircraft design since it has to handle all the engine thrust loads and vibrations during Flight, Take-off and Landing. It also supports auxiliary services such as the Bleed air system for the aircraft cabin heating and cooling, as well as electrical power. The Front engine mount is chosen as a representative use-case to properly explain the methodology proposed in this paper. As shown in Figure 2, the Front engine mount is decomposed into the Frame Hardware (B), the FWD Mount Hardware (C), including purchased/standard hardware (C1, C2, C3), the Upper Mount Pad (D), the Lower Mount Pad (E), the Mount Link (F), the Firewall Hardware (G), and the Yoke (H).

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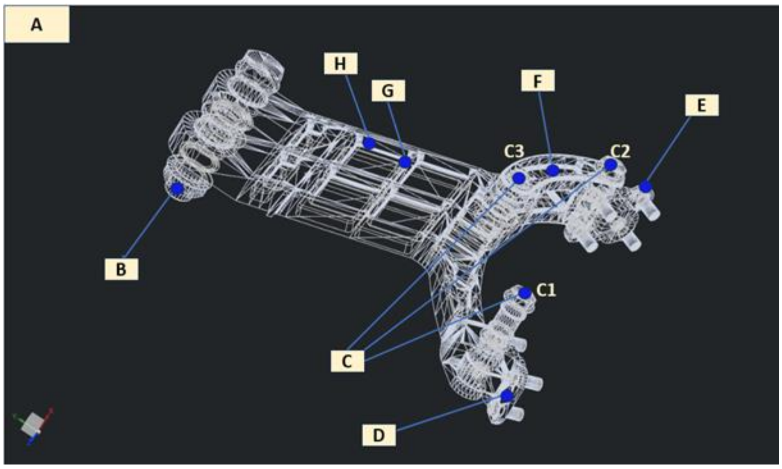
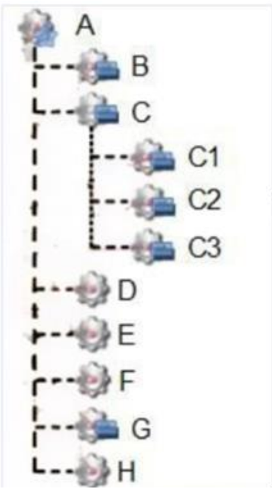


Figure 2. Engine Front Mount Structure Model

2.1. Front Mount Engine EBOM

The structure of the EBOM of the Front Engine Mount including the whole Forward Engine Mount and its attachments design structure in the Pylon of the CRJ700 aircraft. The left-hand side of figure 3 demonstrates the EBOM layered structure, comprising eight main parts from A to H.



EBOM		A	B	C	C1	C2	C3	D	E	F	G	H
	A: FWD Mount											
	B: Frame Hardware	1										
	C: FWD Mount Hardware	1										
	C1: Purchased /STD hardware			1								
	C2:Purchased /STD hardware			1								
	C3: Hardware			1								
	D: Upper Mount Pad	1										
	E: Lower Mount Pad	1										
	F: Mount Link	1										
	G: Firewall Hardware	1										
	H: Yoke	1										

Figure 3. EBOM structure of Engine Front Mount through tree representation (left-hand side) and corresponding DSM-based representation (right-hand side)

We represent the EBOM through a DSM (right-hand side of figure 3), where elements of the matrix correspond to the structural components of the Forward engine mount and 'units' at the intersection of the corresponding rows and columns represent the decomposition relationships. For instance, "units" in the first column represent that the "FWD Mount" is decomposed to the "B: Frame Hardware", "C: FWD Mount Hardware", "D: Upper Mount Pad", "E: Lower Mount Pad", "G: Firewall Hardware", and "H: Yoke". As shown in Figure 2, the Forward Mount Hardware "C" includes "C1", "C2" and "C3" which are purchased/standard hardware parts.

2.2. Front Mount Engine MBOM

The manufacturing process encompasses information about raw materials, tools and assembly sequence, containing all the specifications of the as-designed parts to produce a product. The assembly processes of the engine Front mount can be represented by a properly structured MBOM so that the sequence of assembly is properly represented and linked to all other manufacturing data. The MBOM of the Front Mount is shown in the left-hand side of figure 4 where the sequence of assembly is represented from the bottom to the top, with the final assembly A-MFG-PDT at the top of the MBOM.

The process sequence is divided into three major assemblies in addition to the subassemblies. The whole assembly related to the Front mount is denoted as A-MFG-PDT, composed of MFG-ASSY-003, "Bm", and "Gm"., where "Bm" and "Gm" are manufacturing definitions of the "B: Frame Hardware" and "G: Firewall Hardware" respectively. In turn, MFG-ASSY-003 includes MFG-ASSY-001 and MFG-ASSY-002 and "C3m" (manufacturing definition of the C3: purchased/STD hardware part), In addition to an INST-ASSY that represents the assembling process of the testing equipment which is needed for prototype testing.

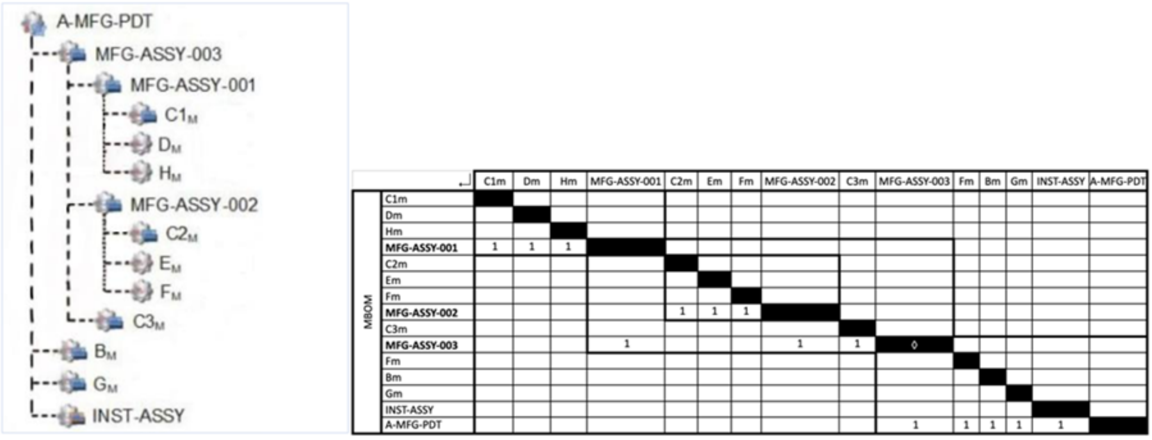


Figure 4. MBOM structure of Engine Front Mount through tree representation (left-hand side) and corresponding DSM-based representation (right-hand side)

To demonstrate the Engine Front Mount assembly process with a DSM, which provides the representation of the assembly sequence (right-hand side of the figure 4). The flow of the processes should be read from the upper left corner of the matrix to the bottom right corner. The "unit" at the corresponding row and column indicates that assembly (represented in a row) has the relation with part/subassembly (represented in column).

Therefore, the assembly sequence begins with connecting "Dm" (Upper Mount Pad) and "Hm" (Yoke) together, using "C1m" (purchased/standard Hardware) as a component. This assembly process results in the creation of sub-assembly "MFG-ASSY-001" (Manufacturing Assembly 001), where "Dm," "Hm," and "C1m" are integral components. In the DSM representation, this process is represented through the "units" at the intersection of "C1m", "Dm" and "Hm" columns with a row of "MFG-ASSY-001".

Similarly, "MFG-ASSY-002" (Manufacturing Assembly 002) is obtained by connecting "Em" (Lower Mount Pad) and "Fm" (Mount Link) with "C2m" (purchased/standard Hardware). In DSM representation this process corresponds to the "units" at the intersection of "C2m", "Em" and "Fm" columns with a row of "MFG-ASSY-002". As a next step, "MFG-ASSY-001" and "MFG-ASSY-002" are connected with "C3m" (purchased/standard Hardware) to get "MFG-ASSY-003" (Manufacturing Assembly 003) as a result. This could be identified through the "units" and the intersection of "MFG-ASSY-001", "MFG-ASSY-002" and "C3m" columns with "MFG-ASSY-003" row. And to get the final assembly of the Engine Front Mount ("A-MFG-PDT") "MFG-ASSY-003" should be connected with "Bm" (Frame Hardware) and "Gm" ("Firewall Hardware Forward Engine Mount"). Since this specific case demonstrates the manufacturing process for development and testing, final assembly as well includes "INST ASSY" (Instrument Assembly). The goal of this process is to assemble the testing equipment which is needed for prototype testing including thermocouples, accelerometers, flowmeters and other specific tools which will be attached to the test stand. That is represented in the last row by "units" at the intersection of "MFG-ASSY-003", "Bm", "Gm" and "INST-ASSY" columns with "A-MFG-PDT" row.

3. EBOM and MBOM integration

The integration of the EBOM and MBOM is highly important for the design and manufacturing process to achieve seamless a Digital Thread. In this specific case, figure 5 illustrates the relationships between the Design and the Manufacturing process for development and testing. However, this specific case can be generalized for any engineering to manufacturing interface. To keep the coherency of the Digital thread among engineering and manufacturing teams, Toche et al. (2017) propose the following set of the links: equivalence, occurrence, and reference links. The structure of connectivity in these links are not isomorphic as the structures of the EBOM and MBOM are different. To ensure the conformity, the part in the manufacturing process is linked through equivalence links to the equivalent latest revisions of the part in the EBOM. In multi-plants manufacturing companies, equivalent links are used to alert manufacturing engineers when a new design iteration is created. In turn, the occurrence link ensures the position of parts in the EBOM and MBOM. The reference link thus enables the parts to be linked to each other in the EBOM and MBOM in a one-to-many relationship.

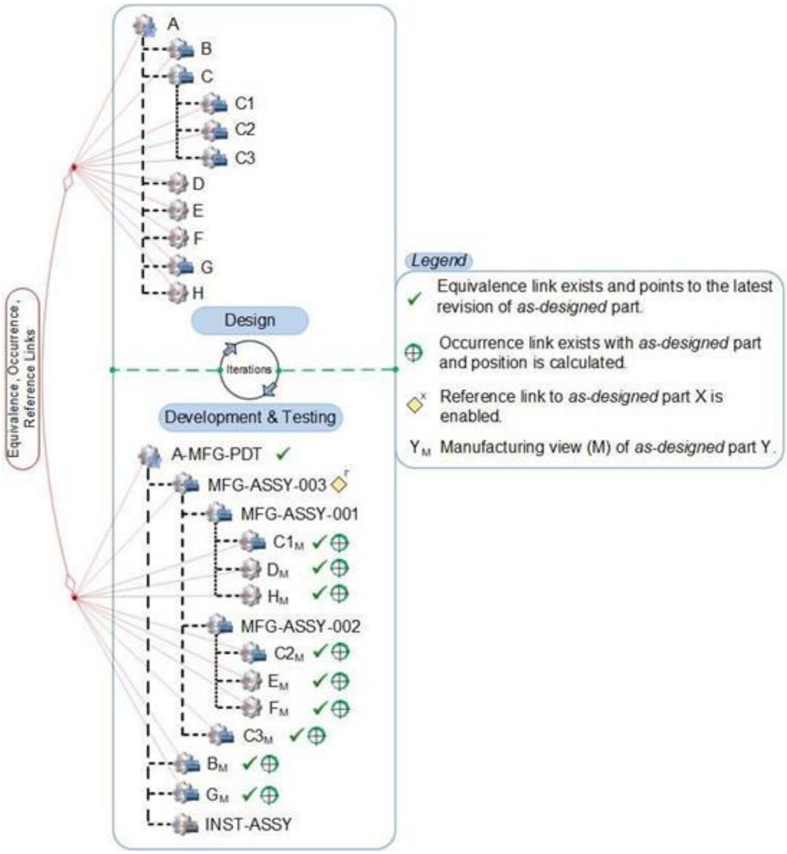


Figure 5. EBOM and MBOM complementary structure of the Front Engine Mount (Toche et al., 2017)

3.1. Representation of EBOM and MBOM integration through MDM

To emphasize the role of the complementarity principles, we applied an MDM approach to represent the cross-domain mapping between the engineering data structure, that is focused on the physical domain, and the manufacturing data structure, that is focused on the process sequence representation. The MDM fully supports the representation of all data that is composed in Figure 5 and at the same time adds more visual clarity.

According to Figure 6, the MDM consists of three zones: 1. The EBOM internal structure, that corresponds to the right-hand side of figure 3, is represented in the orange zone; 2. The MBOM structure, that corresponds to the right-hand side of figure 4, is represented in the blue zone; 3. The EBOM to MBOM relationships are represented in the green zone. It is also important to note that in this paper we only consider the flow from EBOM to MBOM, thus the part that is above the diagonal is empty. The various types of the links represented in the green zone support the precise integration of the EBOM and MBOM.

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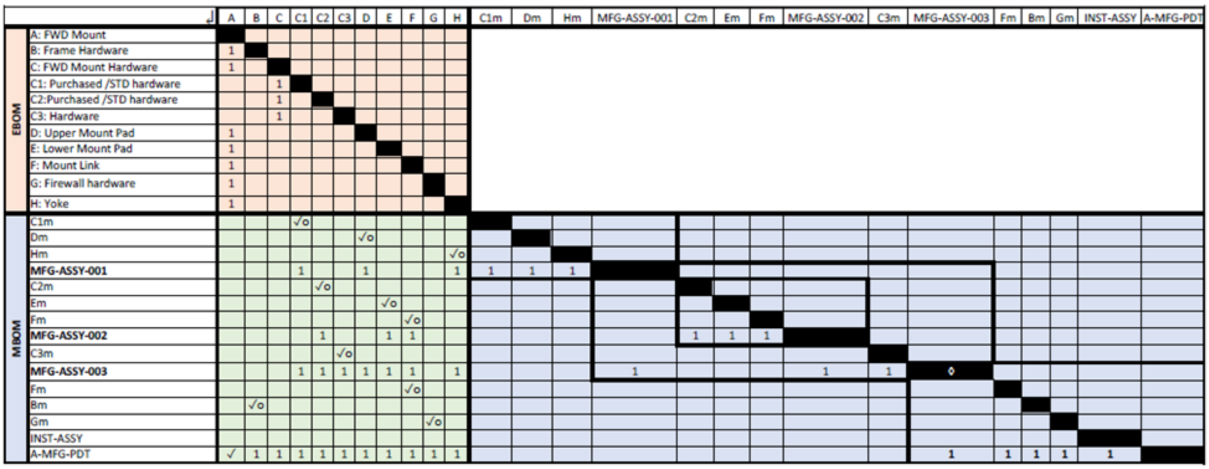

Figure 6. MDM-based representation of EBOM and MBOM integration

The "unit" at the intersection of the corresponding row and column represents that the component of the EBOM has a corresponding definition in the MBOM. With this we could state that the EBOM is affine to the MBOM through the capability of the as-designed parts and their manufacturing process to be put in close relation. It is important to note that relationships between the complementary of the and MBOM could be one to many, and many to one. This aligns with the third principle of complementarity, that corresponds to the presence of sophisticated relationships, that ensures the consistency of the data used in the design and manufacturing lifecycle, thereby supporting the configuration management process. For instance, "C1: Purchased/STD hardware", "D: Upper mount pad" and "H: Yoke" are linked to "MFG-ASSY-001" because this assembly is aggregated from the corresponding manufacturing definitions, such as "C1m", "Dm" and "Hm".

We can see that there is no such correspondence with "MFG-ASSY-001", "MFG-ASSY-002", "MFG-ASSY-003" and "INST-ASSY" since these assemblies are critical for the assembling sequencing and are not present in the EBOM. In turn, "C: Forward Mount Hardware" has no explicit manufacturing definition, as from the manufacturing perspective only the definitions of its structural decomposition of subcomponents such as "C1: Purchased/STD Hardware", "C2: Purchased/STD Hardware", and "C3: Hardware" are relevant for the assembly sequence. Furthermore, "INST-ASSY" is not defined in the EBOM since it is tightly process-related to the information relevant for the assembling process of the testing equipment which is needed for prototype testing. That represents the irreducibility of EBOM and MBOM through the inability to reduce one system to another without losing its essential characteristics — structural decomposition for EBOM and production process sequence for MBOM.

The equivalence link is represented by the sign "✓" at the intersection of the corresponding row and column. For example, "Dm" , which is the manufacturing definition of the as-designed part "D" is equivalent to the latest revision of the as-designed part "D: Upper mount pad". The occurrence link is represented by the sign "o". It essentially gives the information of where exactly the equivalent parts are located. The reference link (denoted with "◊ ") is also shown at the intersection of the row and column of "MFG-ASSY-003". Thus, this approach shows the strength of the interaction and linkage in the complementary information between the designed stage and the manufacturing process, and highlights the role of the complementarity principles in the integration process.

3.2. Configuration management through an MDM-based approach

The MDM approach as well supports the representation of the configuration management process, in order to ensure the accurate flow of data related to the EBOM and the MBOM. An example of the possible configuration management process is presented with the blue arrows in Figure 7. This example implies that some modifications were applied to the as-designed part "D: Upper mount Pad", and, thus, it is required to specify the latest revision of its manufacturing definition in the manufacturing assembly. By navigating through blue arrows, we can identify those changes in part "D: Upper mount Pad" could influence the "MFG-ASSY-001", since the manufacturing definition of "D" ("Dm") is involved in its

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assembly process; this is denoted by the "element" at the intersection of the "D" column with "MFG-ASSY-001" row. As "MFG-ASSY-001" is involved in the assembly process of the "MFG-ASSY-003" and, in turn, "MFG-ASSY-003" is involved in the assembly process of the "A-MFG-PDT", we could track those changes in "D" leading to the changes in assembly processes of "MFG-ASSY-003" and "A-MFG-PDT". This mapping approach could be applied to other as-designed parts as this example aims to pave the approach for tracking the configuration management data. We foresee that the MDM approach could support the consistency of configuration management and enhance the digital thread, since the approach can be scaled to large systems within a software implementation.

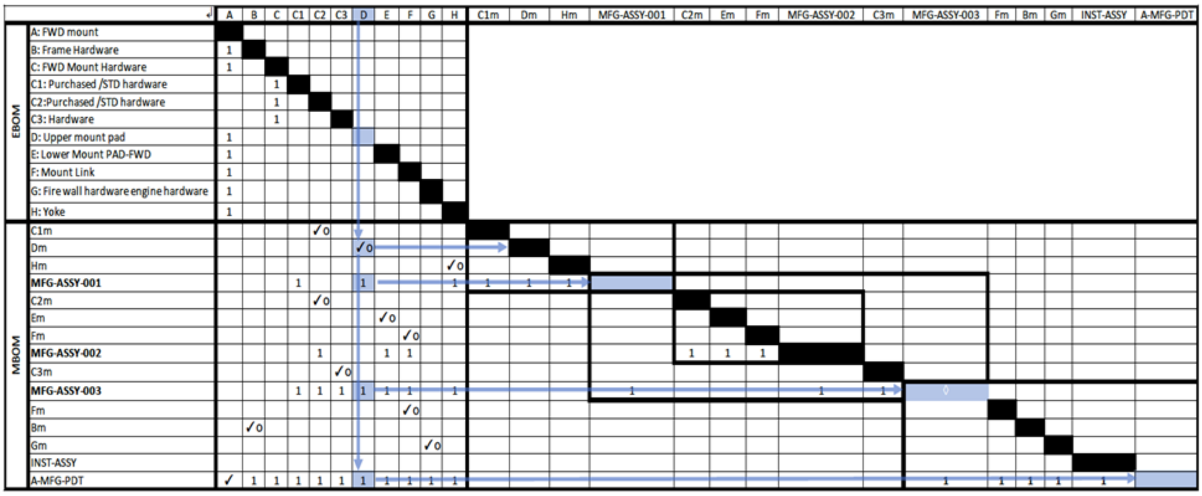

Figure 7. MDM-based representation of configuration management between EBOM and MBOM

4. Discussion and conclusion

Full-scale integration throughout the Digital Thread is essential to ensure efficient functionality and seamless data exchange across the product lifecycle, spanning from conceptual design to detailed design to production and vice versa.

As configuration management is one of the important aspects to achieve a coherent digital thread, the creation of the mapping structure for configuration management data through MDM, fully supports the conformity of EBOM and MBOM data. The users must therefore be supported with proper types of links, data structures and an interactive process to maintain the coherency of the data structures between the engineering and the manufacturing definitions as the development process goes through many revisions and phases.

In conclusion, while our approach contributes to the overall success of configuration management and ensures seamless integration and tracking of relationships between data, supporting upstream data flow in the Digital Thread from manufacturing to engineering, remains an area for future enhancement and exploration. Furthermore, as systems complexity grows, leading to larger and potentially more sparse matrices, ensuring the scalability and efficiency of the approach becomes crucial. The use case presented at this paper serves as an illustrative example, however, scalability and flexibility of MDMs could accommodate growing complexity and evolving requirements during the product development process. Therefore, as a future step, we envision extending this approach to encompass more complex systems supported by large scale databases.

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References

Brovar, Y., Menshenin, Y., & Fortin, C. (2021). Study of system interfaces through the notion of complementarity. Proceedings of the Design Society, 1, 2751–2760. https://doi.org/10.1017/pds.2021.536

Browning, T. R. (2001). Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions. In IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT (Vol. 48, Issue 3).
Elaasar, M., and Neal, A. (2013). LNCS 8107 - Integrating Modeling Tools in the Development Lifecycle with OSLC: A Case Study. In LNCS (Vol. 8107). http://abc.com/toolB/resource/999
Eppinger, S. D., and Browning, T. R. (2012). Design Structure Matrix Methods and Applications. The MIT Press. https://doi.org/10.7551/mitpress/8896.001.0001
Gagné, S., & Fortin, C. (2007). Application of the CMII model to an integrated engineering and manufacturing development environment. International Journal on Interactive Design and Manufacturing (IJIDeM), 1(1), 5–13. https://doi.org/10.1007/s12008-007-0002-8
Gladwin, C. H. (1979). Production Functions and Decision Models: Complementary Models. In Source: American Ethnologist (Vol. 6, Issue 4).
Hedberg Jr, T. D., Bajaj, M., & Camelio, J. A. (2020). Using graphs to link data across the product lifecycle for enabling smart manufacturing digital threads. Journal of computing and information science in engineering, 20(1), 011011.
Hoffman, C. M., and Joan-Arinyo, R. (1998). CAD and the product master model.
The International Council on Systems Engineering (INCOSE), http:// www.incose.org/, Accessed: February 2014.
Kwon, S., Monnier, L. v., Barbau, R., and Bernstein, W. Z. (2020). Enriching standards-based digital thread by fusing as-designed and as-inspected data using knowledge graphs. Advanced Engineering Informatics, 46. https://doi.org/10.1016/j.aei.2020.101102
Maurer, M., and Lindemann, U. (2008). The application of the Multiple-Domain Matrix: Considering multiple domains and dependency types in complex product design. 2008 IEEE International Conference on Systems, Man and Cybernetics, 2487–2493. https://doi.org/10.1109/ICSMC.2008.4811669
Milgrom, P, and Roberts, J. The economics of modern manufacturing: technology, strategy, and organization. Am Econ Rev. (1990) 80:511–28.
OSLC (2023), "Open Services for Lifecycle Collaboration". http://open-services.net/wiki (accessed 10 November2023).
PTC (2024) 'Windchill PLM Software'Available online: https://www.ptc.com/en/products/plm/plm-products/windchill (accessed on 9 February 2024).
Steward, D. V. (1981). The Design Structure System: A Method for Managing the Design of Complex Systems. In IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT (Issue 3).
Toche, B., Mcsorley, G., Pellerin, R., & Fortin, C. (2017). A framework to support collaboration during prototyping and testing. In Int. J. Product Lifecycle Management (Vol. 10, Issue 4).