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Integrating multiple industry 4.0 approaches and tools in an interoperable platform for manufacturing SMEs

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ABSTRACT

Small and medium-sized enterprises (SMEs) often struggle to optimize their production processes and products due to limited resources and lack of expertise in technological solutions. To address this issue, this research work presents a multi-purpose platform that can be used by SMEs as easy-to use support tool to run what-if analyses to optimize their products and production processes design. The platform fulfills the requirements of interoperability, accessibility, and usability and is built upon a layered infrastructure, consisting of specific modules within its Decision-Making Layer, Data Exchange Layer, and User Management Layer. The platform integrates several software, including Plant Simulation, Autodesk Inventor Nastran, and Autodesk Inventor Nesting, to simulate production processes, to run finite element analysis, and to optimize raw material utilization. The interoperability and data exchange are ensured through the adoption of FIWARE, an open-source framework for IoT platforms, which enables the harmonized representation of data formats and semantics among different applications and software within the platform. The User Management Layer allows SMEs to easily interact with the platform, making it an easy-to-use tool even for those with limited IT competencies. A case study conducted by an SME in the furniture sector demonstrated the platform's effectiveness in achieving optimal design and production of a new bookcase, resulting in increased efficiency, reduced costs, and improved profitability. The modular structure of the platform enables potential future integration of additional modules, such as quality control, supply chain management, etc., further enhancing its capabilities and potential benefits for SMEs. The proposed multi-purpose platform represents a valuable tool for SMEs to optimize their production processes and products and to overcome the limitations due to their limited resources and expertise in technological solutions.

1. Introduction

The industry 4.0 (I4.0) paradigm is changing business practices, through the spread of new concepts and technologies such as the Industrial Internet of Things (IIoT), cyber-physical systems, big data, digital twins, cloud computing, artificial intelligence (Boyes et al., 2018; Wang et al., 2022). Nowadays, companies need to effectively and efficiently exploit the opportunities offered by all these innovations to be competitive on a global basis. In this context, the manufacturing industry is continually characterized by new challenging issues such as maintaining a high quality and level of customization of the product, while ensuring limited costs (Adamczyk et al., 2020). Basically, in recent years there has been a shift away from standardized and mass manufacturing to production more oriented to individual customer needs. This has made planning and executing business practices very complex and challenging. The ongoing digital transformation is completely redefining the way of designing, producing and distributing products towards more sustainable and resilient manufacturing systems and supply chains (Rajesh, 2021; Ambrogio et al., 2022).

One of the main consequences of the advent of I4.0 technologies concerns the significant growth of data generated, not only in terms of volume, but also and above all in terms of variety. A large number of systems and therefore actors are today connected to each other to exchange data and information (e.g., suppliers, customers, other stakeholders, etc.). For this exchange to be successful, it is necessary to guarantee adequate levels of interoperability, considering that each system has its own rules and communication protocols. The term interoperability indicates "the ability of two or more systems components to exchange information or to and use the information that has been exchanged" (Chapurlat and Daclin, 2012). The lack of coherence

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from a semantic and/or syntactic point of view can make collaboration, communication and decision-making very difficult during the entire product life cycle (Ameri et al., 2022). Common examples of Semantic Interoperability Conflicts (SICs) are (Melluso et al., 2022): different interpretations of the same domain (e.g., two or more different acronyms for the same concept, same term to represent concepts with different meaning), different attributes to represent the same concept in different sources, different representations in terms of scale or precision value for refer to the same concept (Chen et al., 2008; Jirkovský et al., 2016; Orgun et al., 2008). In this challenging context, FIWARE represents one of the most promising frameworks. It is an open-source solution, which provides users with various tools such as standard Application Programming Interfaces (APIs), enablers (generic and specific), data models, aimed at the effective and efficient building of smart applications in several domains such as Industry 4.0, Smart Cities, Agri-Food, Energy (FIWARE, 2023). FIWARE is able to offer various functions, according to the user's needs, such as management of context information, translation of multiple communication protocols into a single basic protocol, support in the design and development of smart ecosystems (Alves et al., 2023). To date, significant efforts have been made in using FIWARE to support smart farming (López-Riquelme et al., 2017; Zamora-Izquierdo et al., 2019). Interesting applications are present in various other areas such as smart cities (Araujo et al., 2019), education (Zaharov et al., 2018), energy (Terroso-Saenz et al., 2019), healthcare (Fazio et al., 2015), supply chain management (Muñuzuri et al., 2020). However, today it represents a promising tool to enable and support the Digital Twin paradigm. Indeed, the use of FIWARE is crucial especially in the twinning process, which involves the physical and virtual world (Conde et al., 2022): any change of the physical entity is captured through an IoT sensor and translated into an update in the virtual world; correspondingly, each update on the virtual entity is translated into an update of the state of the physical entity by means of an IoT actuator. In this context, the IoT Agents offered by FIWARE can work as a bridge between the different protocols used in the real environment (different standards could be present, considering the multitude of sensors existing today) and the virtual environment. Although there is today a very high interest around FIWARE, there is still much to do: the contributions are all very recent and efforts are needed for this solution to become mature and recognized. Currently a query on Scopus, generically using "FIWARE" (field: "Article title, Abstract, Keywords) generates less than 300 results. Among these documents, none explicitly and specifically focuses on the needs of the Small and Medium Enterprises (SMEs).

In accordance with the EU recommendation 2003/361, SMEs are firms with a turnover of less than 50 million euros and fewer than 250 employees. In the scientific literature, many I4.0-driven solutions have been recently designed to support business operations (Zutshi and Grilo, 2019; Mourtzis, 2020; Sahal et al., 2020; Kabugo et al., 2020; Longo et al., 2022; Christou et al., 2022; Tolio et al., 2023), but only a few have been thought to meet the specific needs of SMEs. Liu et al. (2022) designed and implemented DIGICOR, an I4.0 platform to dynamically support collaborations between SMEs along supply chains. Among the services offered, support in production planning and control, and in logistics. Collaboration issues were also addressed by Cotrino et al. (2021), who designed and developed Industry 4.0 HUB, a web-based platform aimed at transferring knowledge to SMEs in a cooperative manner. Kumari et al. (2015) proposed a self-adaptive and multi-agent system to help SMEs in the decision-making process, with a focus on outsourcing related decisions. Integrating the new I4.0 tools into SMEs is extremely challenging for numerous reasons, as reported by Orzes et al. (2020), who detected five main types of obstacles: (i) the vast majority of SMEs have significant constraints from a financial point of view, which limit their ability to invest in innovative technologies, whose expected benefits may not be clearly known; (ii) the limited level of advanced knowledge and technical skills can discourage the adoption of very complex and/or still little-known I4.0 technologies; (iii) another reason for the limited diffusion of the I4.0 paradigm in SMEs concerns the lack of adequate IT infrastructures in terms of connectivity (Mourtzis et al., 2021) and platforms/architectures capable of ensuring interoperability and compatibility between systems (Müller et al., 2018); (iv) moreover, many SMEs rely on not very well skilled managers, who are quite conservative and unwilling to introduce risky innovations; (v) the processes of integration and consequent implementation of new technologies within already existing SMEs can be very complex, in the absence of adequate management and experience in managing changes in business models (Sjödin et al., 2018).

Table 1
Comparison between this paper and the most relevant ones in the literature in terms of I4.0-related platforms.

Reference	Focus on Interoperability	Modularity	Focus on SMEs	Integration with commercial software	Real case study
Terroso-Saenz et al. (2019)	✓	✓			✓
Zutshi and Grilo (2019)		✓			
Coito et al. (2020)	✓	✓		✓	✓
Hasan and Starly (2020)					✓
Cotrino et al. (2021)		✓	✓	✓	
Han and Trimi (2022)	✓		✓		✓
Christou et al. (2022)	✓	✓			✓
This paper	✓	✓	✓	✓	✓

2. Research gaps and our contribution

With the aim of identifying the main current research gaps, the most relevant and recent I4.0 platforms currently existing in the literature were analyzed and classified in Table 1, based on 5 fundamental dimensions:

- focus on interoperability: the feature is considered present if it is explicitly explained how to guarantee interoperability; the absence of the feature in Table 1 does not necessarily imply that the platform is non-interoperable, but rather that this topic is not the focus of the paper, therefore it is not very well explained.
- modularity: the feature is considered present if the platform has a modular structure;
- focus on SMEs: the feature is considered present if the platform has characteristics that meet the specific needs of SMEs;
- integration with commercial software: the feature is considered present if integration with one or more commercial software is explicitly mentioned.
- Real case study: the feature is considered present if the platform is validated through one or more case studies.

The symbol (✓) was adopted to indicate that a certain feature is present within each paper taken into consideration.

Summarizing, there is a need for solutions that can support the transition of SMEs towards the adoption of Industry 4.0 technologies. This need is urgent because they need to remain competitive in a constantly changing landscape (Masood and Sonntag, 2020).

From the analysis of the scientific literature, some relevant research

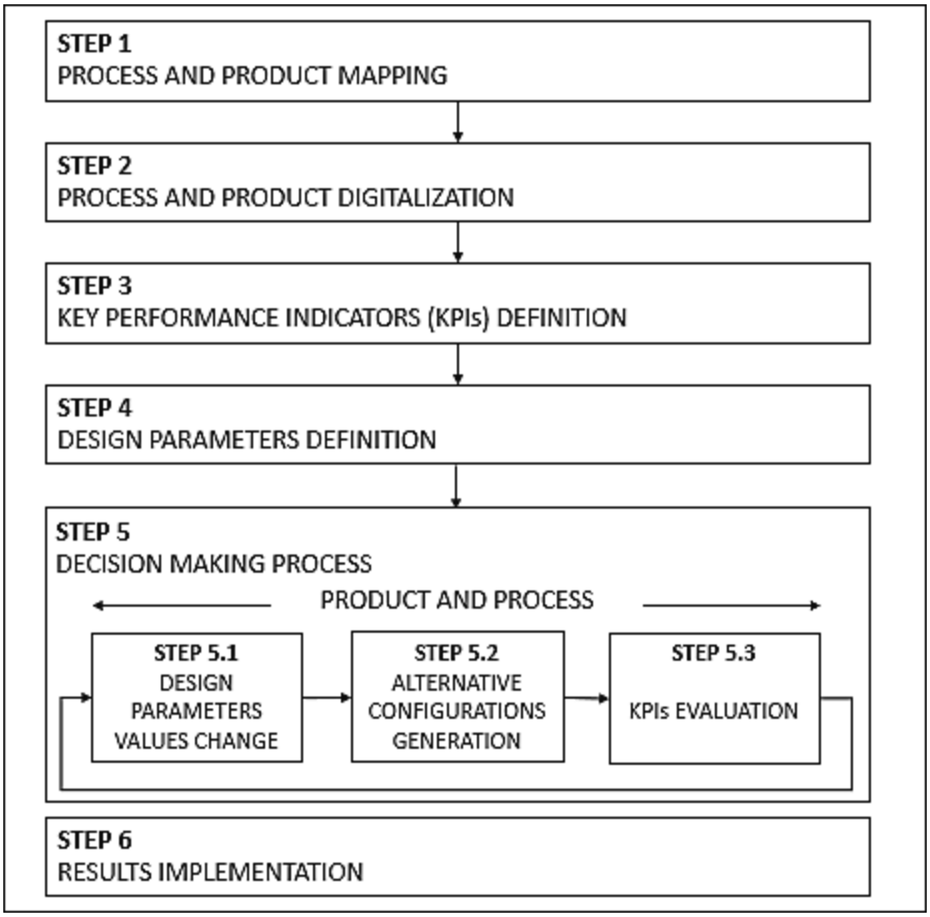

Fig. 1. Reference methodological approach.

gaps clearly emerge:

- currently, there is a shortage of ready-to-use I4.0 solutions for SMEs, which are often unable to implement this novel paradigm effectively and efficiently, due to significant financial, technical, social, and cultural constraints (Orzes et al., 2019);
- despite the recent proliferation of I4.0-driven solutions, there is still little focus on interoperability issues. This makes their lifecycle and reusability extremely limited, as they cannot interface properly with additional internal or external business modules. According to Ameri et al. (2022), one of the keys to the successful implementation of Industry 4.0 paradigm is the ability to effectively and efficiently collect, process, analyze, communicate and store data;
- FIWARE is an extremely promising solution, but significant research efforts are still needed for it to reach full maturity and be recognized on a large-scale. Furthermore, despite its countless benefits, it is currently not known to SMEs;
- there is a need for general I4.0 platforms/architectures, which encompass multiple functionalities, with the aim of limiting the number of interfaces and facilitating data exchange.

To overcome the research gaps highlighted above, this paper proposes an I4.0 multi-purpose platform, aimed at supporting SMEs in the transition towards the new paradigms of the fourth industrial revolution. The platform aims to increase the adoption of the new Industry 4.0 concepts in the SMEs, through its high usability, to the point that even users with poor IT knowledge can use it effectively and efficiently, through a web-based interface. Furthermore, the proposal is based on the use of FIWARE to face the current challenges related to interoperability. Despite of the numerous theoretical solutions present in the literature, the platform is tested and validated with promising practical results on a real-life case study, which refers to the furniture sector.

The rest of this paper is organized as follows. Section 2 concerns the materials and methods, therefore the proposed I4.0 multi-purpose platform is presented and described. In Section 3, concerning the calculation, the real-life case study is described, the results of which are reported in Section 4. Conclusions are in Section 5.

3. Materials and methods

The proposed research work has been devoted to develop a multi-purpose platform that can be used by SMEs as support tool in order to optimize the design of production processes and products. The starting point of the research activities has been the definition of a reference methodological approach that outlines the roadmap for the design of the conceptual architecture being used to develop a concrete technological platform. The proposed platform, based on a layered infrastructure, combines different modules and it fulfils the requirements of interoperability, accessibility and usability. The modules can easily communicate each other by exchanging input (design parameters) and output (KPIs) data; the syntactic and semantic interoperability makes the platform usable by different companies adopting also different internal procedures and standards. The platform is also easy to use and does not require specific technical competences. In this section, the authors present a detailed description of the research work material and methods. In particular, section 2.1 presents the methodological reference approach whose technological translation results in the proposed multi-purpose platform being described in section 2.2.

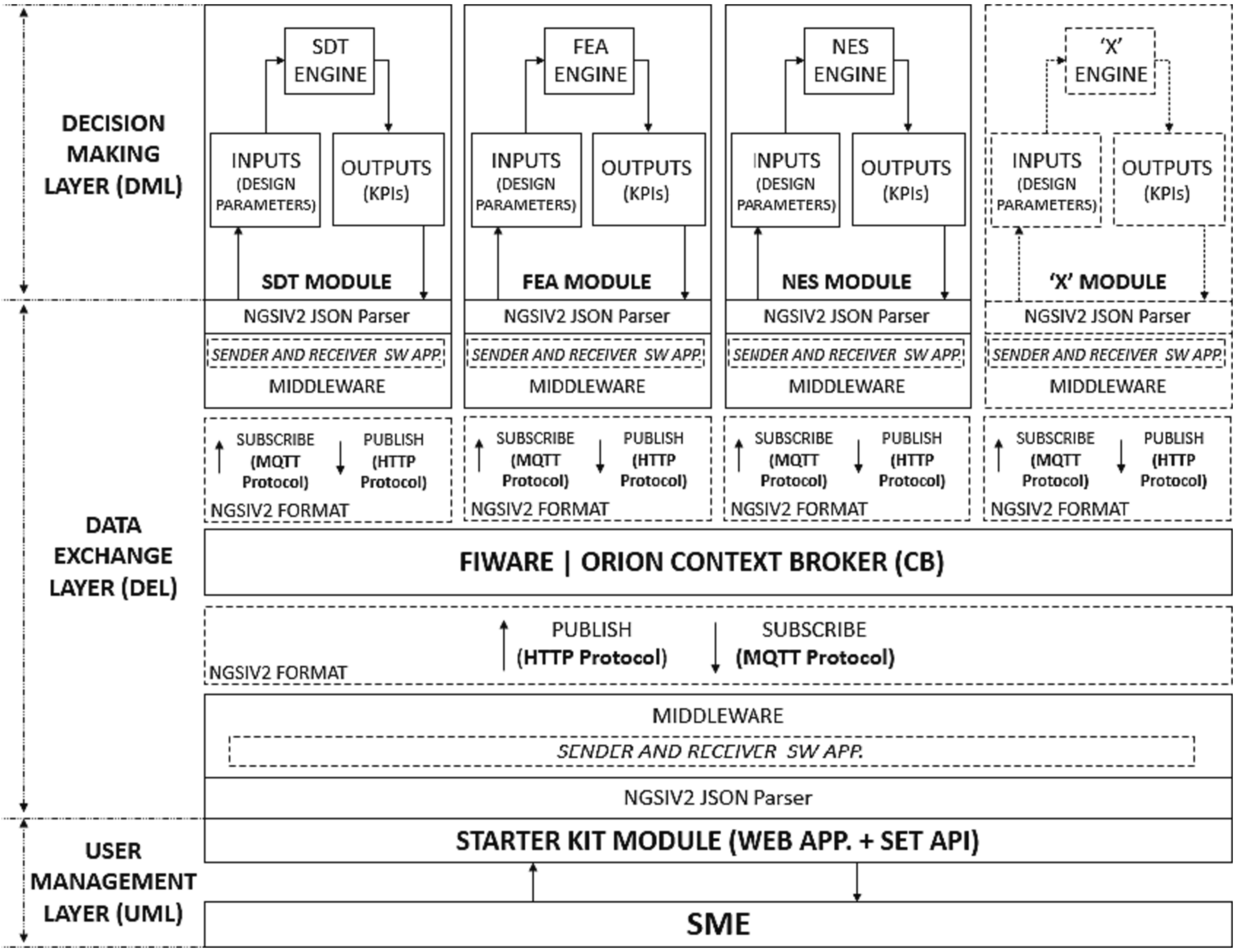

Fig. 2. Multi-user and multi-purpose platform infrastructure.

3.1. Reference methodological approach

The reference methodological approach can be conceptualized in the following steps:

- STEP1: PROCESS AND PRODUCT MAPPING

This step aims at assessing the current status of SMEs production process and product design features. Production flow and layout, equipment and tools, machinery type, machine and workers number, workers characteristics, work methods and operations, products dimensions and weight, materials, sub-components number and quantity can be considered as information and data which may be used to define an “AS IS” status. It is important to remark that the selection of the information and data to be collected changes based on the reference context being considered.

- STEP2: PROCESS AND PRODUCT DIGITALIZATION

Based on the data and information collected during the STEP1, next step is to proceed with the digitalization of SMEs production processes and products. The idea is to create digital mirrors of the real systems (processes and products) which can be used for optimization purposes. Software and tools being used for the digitalization are mentioned in section 2.2.1.

- STEP3: KEY PERFOMANCE INDICATORS (KPIs) DEFINITION

The reference methodological approach proceeds by the definition of the KPIs which SMEs would like to monitor and optimize. Among the others, flow time, machine and workers utilization rate may be examples of KPIs characterizing the production processes, while, for instance, product physical characteristics such as materials deformations levels or sub-components number that can be produced by using the same raw materials quantity can be noted as KPI examples for product design optimization. KPIs definition can definitely vary according to the reference context and company’s targets. The full list of the defined KPIs for the developed platform is reported in Appendix (please refer to Table A1).

- STEP4: DESIGN PARAMETERS DEFINITION

At this stage the proposed approach requires an analysis for detecting the main design parameters that could have an impact to the production processes and product KPIs. Workers number and efficiency or production batch sizes may be good examples of design parameters related to the production processes, while dimensions and material types can be listed as design parameters for products design optimization. As for the KPIs definition, the selection of the design parameters is definitely specific to the reference context. The complete list of the proposed design parameters within the platform is reported in Appendix (please refer to Table A1).

- STEP5: DECISION MAKING PROCESS

The decision-making process is the core of the proposed reference methodological approach and it enables a set of what-if analyses to improve and optimize the KPI based on the variation of the design parameters values. The conceptual architecture of the approach results in a sort of cycle of continuous performance improvement carried out by SMEs, in a digital way, by means of the proposed platform: at first step, the current state of the production process and product is assessed in terms of the selected KPIs (STEP 5.1 in Fig. 1), then alternative manufacturing process and product configurations are generated by changing the values of design parameters (STEP 5.2 in Fig. 1) and, finally, the impact of those configurations to the selected KPIs is evaluated (STEP 5.3 in Fig. 1). The cycle can be repeated till the KPIs are optimized.

- STEP6: RESULTS IMPLEMENTATION

The implementation in the physical systems of the design parameters values leading to the KPIs optimization of the production processes and products completes the proposed approach.

The aforementioned approach is depicted in Fig. 1.

3.2. The multi-purpose platform

The technological translation of the conceptual architecture (discussed in section 2.1) results in the development of the multi-purpose platform. End users can easily access the platform through a Web Application (Web App), thus beginning a what-if analysis process devoted to improve and optimize the product and/or production process KPIs. Basically, SMEs can select, in the Web App, specific product and/or production process design parameters, change their values and ask the multi-purpose platform for the quantitative evaluation of the effects of those design parameters to the selected KPIs. Design parameters values are distributed along the platform infrastructure to the modules. The platform modules that receive those data, implement the design parameters values in their application and run the simulations. The simulation runs provide as output updated KPIs values which are sent back from modules to the end users through the Web App. The end users can assess the KPIs values and decide whether to keep the design parameters values (which have been given from SMEs as input to the platform to get the update KPIs values) or to start a further optimization run.

The platform is based on a layered infrastructure whose preliminary view is depicted in Fig. 2. The infrastructure is characterized by three layers: the Decision-Making Layer (DML), the Data Exchange Layer (DEL) and the User Management Layer (UML). Looking at Fig. 2 from a top-down perspective, DML consists of the Simulation based Digital Twin (SDT) module, the Finite Element Analysis module (FEA) and the Nesting module (NES), DEL leverages on the open standards-based cloud FIWARE and UML consists of the Starter Kit module. It's important to note that the platform has been intentionally designed to be modular. Consequently, within the DML, the potential exists for the incorporation of additional modules in the future, based on the evolving requirements and demands of manufacturing systems. Examples of such modules include those for quality control and supply chain management. Nevertheless, it's important to highlight that in the current stage of platform development, specific software for these modules, along with the corresponding design parameters and KPIs, have not yet been selected. These decisions will be made as part of future research, as outlined in the conclusion. Fig. 2 includes a generic module denoted as 'X' with a dashed line to illustrate the platform's adaptability and potential for modularity.

Furthermore, system latency, which refers to the time it takes to respond to a user's request, and the level of end users' expertise required to provide necessary input, can be also quantified. The transmission times between UML and DEL (and vice versa), as well as between DEL and DML (and vice versa), are in the order of milliseconds. Concerning the processing times of each module within the DML, these are typically in the order of seconds. Among these modules, the SDT module is the most critical in terms of processing time, as it depends on the complexity and duration of the production process. However, in order to minimize this processing time, the authors have configured the SDT module to operate at maximum simulation speed by utilizing a feature called 'Start fast forward simulation,' which is provided by the software employed for its development (see Section 2.2.1). Consequently, the overall time from when an end user clicks the button to send process/product design parameters values to when they receive a response from the platform falls within the range of seconds.

As for the end user experience required to use the platform, the level of IT knowledge needed is basic. No specific or deep IT expertise is necessary, and the interaction is similar to using a standard web page online. However, end users are expected to possess expertise in their respective domains of work. They should be knowledgeable about manufacturing system production processes and products in order to select and configure the design parameters correctly. Additionally, an understanding of manufacturing system KPIs is essential to make informed decisions.

Following, in sections 2.2.1, 2.2.2 and 2.2.3, the layers description is presented, while section 2.4 lists and shortly present the software and hardware used for the development and the implementation of the platform.

3.2.1. Decision-Making Layer (DML)

The DML enables to run products and production processes simulations in order to evaluate the quantitative effects of selected design parameters on several KPIs. Basically, each module within this layer, receives design parameters values as input, run either products or production processes simulations and provides KPIs values as output, thus enabling end users to carry out a set of what-if analyses devoted to the products and production processes optimization. The DML consists of the following 3 modules:

- *SDT module*: this module recreates the simulation model of the real SMEs' production processes with the aim of carrying out the quantitative evaluation of the effects of the design parameters on the production processes KPIs. Plant Simulation from TECNOMATIX is the software that has been integrated within the platform in order to develop the simulation models. Further information on Plant Simulation software can be found at https://www.dex.siemens.com/plm/tecnomatix/plant-simulation;
- *FEA module*: this module aims at running finite element analysis (FEA) in order to either properly design new products from a structural point of view or to improve the structural design of existing ones. Autodesk Inventor Nastran is the software that has been integrated within the platform to conduct FEA studies. Further information on Autodesk Inventor Nastran can be found at https://www.autodesk.com/products/inventor-nastran/overview?term=1-YEAR&tab=subscription;
- *NES module*: this module has been developed to conduct nesting studies in order to optimize efficiency in terms of flat raw material yield in the manufacturing process of a product. Basically, SMEs can assess different products design in terms of product dimensions with the aim at optimizing the raw material utilization rate. Based on the data received in input, the module generates a series of suggested nest aiming at reducing raw material wastes and therefore costs. Autodesk Inventor Nesting is the software that has been integrated within the platform in order to carry out the nesting studies. Further information on Autodesk Inventor Nesting can be found at https://www.autodesk.com/products/inventor-nesting/.

3.2.2. Data Exchange Layer (DEL)

One of the main research issues to be tackled by the authors is that applications and software behind each platform module are neither syntactically nor semantically interoperable and therefore not able to

Table 2
Number of design parameters and KPIs.

DML	Design parameters # (input data #)	KPIs # (output data #)
SDT Module	8	7
FEA Module	7	4
NES Module	15	4

communicate as well as to exchange data each other. In order to proper address and solve this issue the multi-purpose platform leverages on FIWARE (further information on FIWARE can be found out at https://www.fiware.org/), an open-source framework for IoT platforms whose aim is to build sustainable ecosystems for smart solution development that, through the joint use of standard components and architectures, enables interoperable data exchange among the platform modules as well as between the platform and the outside world (i.e., SMEs). The interoperable data exchange is guaranteed by the adoption of data models, which define the harmonized representation of data formats and semantics being used by applications and software within the platform. A data model can be defined as a list of data that need to be processed by each platform module. For each platform module, two data models have been defined: the first one to manage the data in input to the module (i.e., design parameters) and the second one to manage the data in output from the module (i.e., KPIs). A data model consists of a list of attribute and types; an attribute identifies either the design parameters or the KPI that can be processed by a module, while the type represents a classification of type of data (i.e., int, double, Boolean, etc.) that an attribute can hold and that can be easily interpreted by a computer system. Table 2 offers an overview of the number of design parameters and KPIs for each DML module, while the data models details including descriptions, attributes and types is reported in Table A1, in the Appendix.

Following the data exchange flow within the platform is detailed. The data flow management involves the use of FIWARE's Orion Context Broker (CB) component. The CB has the following functionalities: (1) receive data from the modules, (2) store the received data, and (3) send the data to the modules. Basically, the CB component can be seen as a message dispatcher through which the different platform modules can communicate each other. Each module can send data to the CB through the Sender software application (the sending operation is named *publish*) and, at the same time, receive data from the CB through the Receiver software application (the receiving operation is named *subscribe*). The aforementioned software applications are implemented within the Middleware component located within the modules. Each module can send data to the CB and receive from the CB the data for which a subscription has been done. Moreover, it has to be pointed out that the CB can receive and send data only in NGSIV2 format, while each module processes data in its own format that may differ from the NGSIV2 format. Therefore, to ensure the data exchange interoperability among the modules, a NGSIV2 JSON Parser software application has been integrated within each module. This application has the task of transferring data from the module specific format into the NGSIV2 format and vice versa. In the case where a module sends data to the CB, the NGSIV2 JSON Parser application transfers the data from the module-specific format to the NGSIV2 format, thus making it readable to the CB. Conversely if it is the CB that needs to send data to a module, the NGSIV2 JSON Parser application transfers the data from the NGSIV2 format to the module-specific format, thus making it readable to the module. As an example, Fig. 3 depicts, on the left side, a data NGSIV2 format for a *publish* operation from the Web App to FIWARE (related to the input data to be sent to the FEA module) and, on a right side, a data NGSIV2 format for a *publish* operation from the FEA module to FIWARE (related to the output data to be sent to the Web App).

3.2.3. *User Management Layer (UML)*

This layer results in the development of a starter kit module, whose main goal is to allow SMEs to easily interact with the platform. The starter kit module consists of a Web App and a set of API. The Web App allows the SMEs to submit and receive data, while the API set supports the data exchange flow with the platform. As far as the Web App development is concerned, the authors efforts have been similarly addressed to both Web App Back-End and Front-End design and implementation. The Back-End rules basically all the functionalities (e.g., end users' profile creation, log-in/log-out process, etc.) offered by the platform and it includes as well the server on which the Web App runs and the database with its related tables for managing the data and which are uploaded to the platform. The Front-End consists of ad-hoc and easy to use graphic users' interfaces (GUI), whose detailed description is reported in section 3.2. As far as the set of API is considered, it consists of a set of methods whose implementation has been necessary in order to establish the connection between the Web App Back-End and FIWARE,

```
{ ⊟
   "actionType":"append",
   "entities":[ ⊟
      { ⊟
         "id":"company.FEA.inputFEA",
         "type":"inputFEA",
         "cadModel":"http://multipurposepl …
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         "outputsControllsmaxDeformation":1,
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         "LoadType":"DISTRIBUTED",
         "loadDirection":"NORMAL TO SURFACE",
         "degreesOfFreedom":"FIXED"
      }
   ]
}
```

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{ ⊟
   "actionType":"append",
   "entities":[ ⊟
      { ⊟
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         "strain":"MIAGCSqGSIb3DQEHA6CAMIACAQAxgcQwgc …
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         "contourDisplacement":null,
         "maxDeformation":0.415
      }
   ]
}
```

Fig. 3. Data NGSVI2 format for publish and subscribe operations.

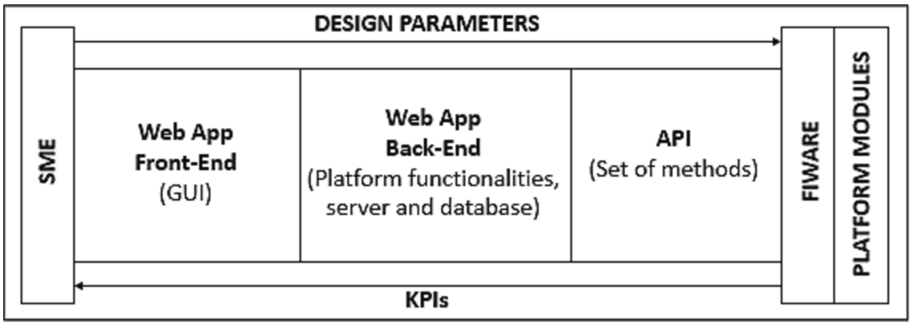


Fig. 4. Data flow high-level architecture.

thus allowing the operative transfer of data from SMEs to the platform modules and vice versa. Fig. 4 depicts a high-level architecture of the data flow between SMEs and the multipurpose platform.

3.2.4. *Software and hardware infrastructure*

This section aims at consolidating and briefly presenting the list of hardware and software components that were used for the development of the platform. While some of these elements are already individually introduced and discussed within various sections of this research work, it is definitely beneficial to offer a short summary here, thus providing the readers with quick and easy access to this information.

For the hardware setup, the platform employs three distinct servers. One server is dedicated to hosting the Web App, while another serves as the infrastructure for FIWARE. The third server is tasked with supporting all three DML modules, which include the SDT module, FEA module, and NES module. For the development of the Web App, the authors have employed Laravel, a robust web application framework (further details about Laravel can be found at https://laravel.com). Among the technologies of this framework, MySQL has been used to deploy the Web App database, Hypertext Preprocessor (PHP) as scripting language to implement the processes logics behind the Web App (Back-End) and HTML Visualization together with Bootstrap and jQuery to develop Web

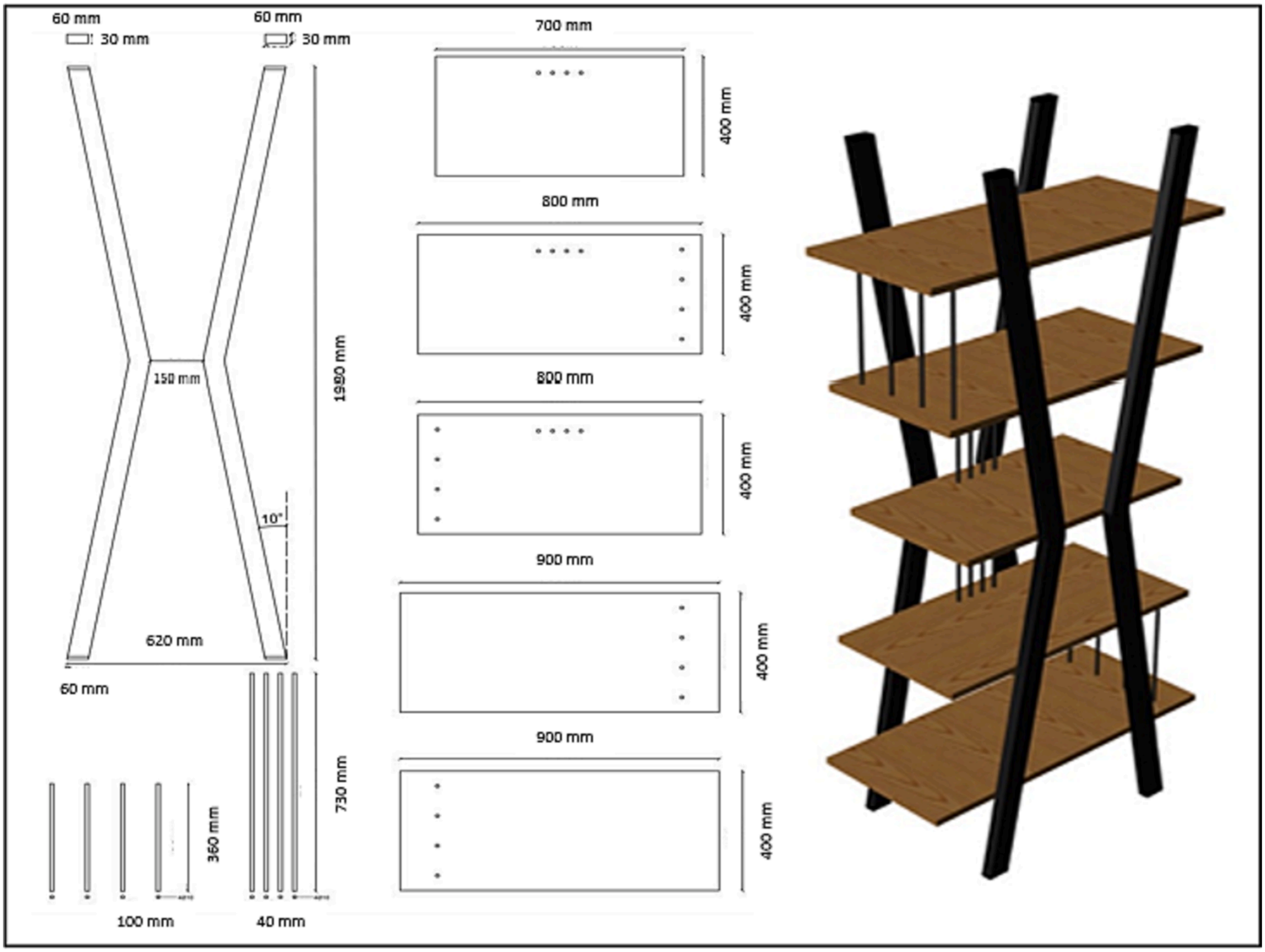


Fig. 5. Bookcase CAD model and sub-components main dimensions.

App graphics (Front-End). Moving forward, each DML module has been developed using specialized software. The SDT module leverages Plant Simulation from Tecnomatix, the FEA module is built upon Autodesk Inventor Nastran and finally the NES module utilizes Autodesk Inventor Nesting (see section 2.2.1).

The interoperable data exchange between the DML modules and the Web App is facilitated by the use of FIWARE, an open-source framework tailored for IoT platforms (see section 2.2.2). Finally, to ensure the data flow, the platform employs specific communication protocols: HTTP is used for data transmission from the Web App to FIWARE and from the DML modules to FIWARE, while MQTT is implemented for data exchange from FIWARE to the Web App, as well as from FIWARE to the DML modules, as illustrated in Fig. 2.

4. Calculation

This section presents an application of the multi-purpose platform conducted by a SME, located in Calabria (Italy) and operating in the furniture sector. The objective of this case study is to showcase the validity and potentiality of the developed platform, by presenting its application for the optimization of a new bookcase design and the optimization of its production line. Through this case study, the authors aim at demonstrating how the use of a multi-purpose platform can help SMEs to achieve their business objectives, by enabling them to develop and manufacture products more efficiently and effectively. The following sub-sections detail the use of a platform to optimize the design and the manufacturing process of the bookcase through the application of the platform modules. Section 3.1 presents the reference context, including a description of the bookcase, its manufacturing process as well as the objectives intended to be achieved by using the platform. Sections 3.2, 3.3, and 3.4 describe respectively the application of specific modules to achieve these objectives. Section 3.2 outlines the use of the of the SDT module being used to define the manufacturing process design guidelines. In section 3.3, the FEA module is used to perform finite element analysis for structural design purposes. Lastly, section 3.4 details the application of the NES module to identify the most efficient arrangement of the bookcase sub-components (shelves) on a raw material sheet in order to minimize waste and reduce costs.

4.1. Reference context

This section presents the design and the technical features of the bookcase, the production steps to manufacture it and the objectives that the SME aims at achieving by using the multi-purpose platform.

Bookcase design and technical features

The product in question is a new bookcase that is currently being developed by the SME. The design and technical features of the bookcase have already been established, with the exception of the thickness of the shelves. The bookcase consists of five oak shelves, four feet, and eleven aluminum tubes. The shelves have been designed with different shapes and dimensions to optimize weight distribution and enhance the overall structural dynamics of the bookcase. Fig. 5 depicts on the right side the CAD model and on the left side the dimensions of each of its main components.

The shelves are positioned at a distance of 350 mm from each other, with the central shelf measuring 700 mm in length (L) and 400 mm in depth (D). The other two sets of shelves measure 800 mm (L) x 400 mm (D) and 900 mm (L) x 400 mm (D), respectively. To ensure stability, each foot of the bookcase is secured to the structure through the use of standard wood screws and five brackets per foot. The bookcase's design is not yet finalized, as the thickness of the shelves remains to be determined by using the FEA module.

Bookcase production process

The production steps for the manufacturing of the bookcase have been previously identified by the SME, and an initial configuration of the plant resources has been already established. However, it is still necessary to finalize, optimize and validate the configuration of plant resources (i.e., number of workers, number of machines, etc.), which will be achieved by utilizing the SDT module. The following macro-operations have been identified.

- Macro-operation 1A: oak panel manufacture;
- Macro-operation 2A: aluminum tubes manufacture and assembly;
- Macro-operation 3A: components packaging before delivery to final customers;

A brief description of each macro-operation is reported below.

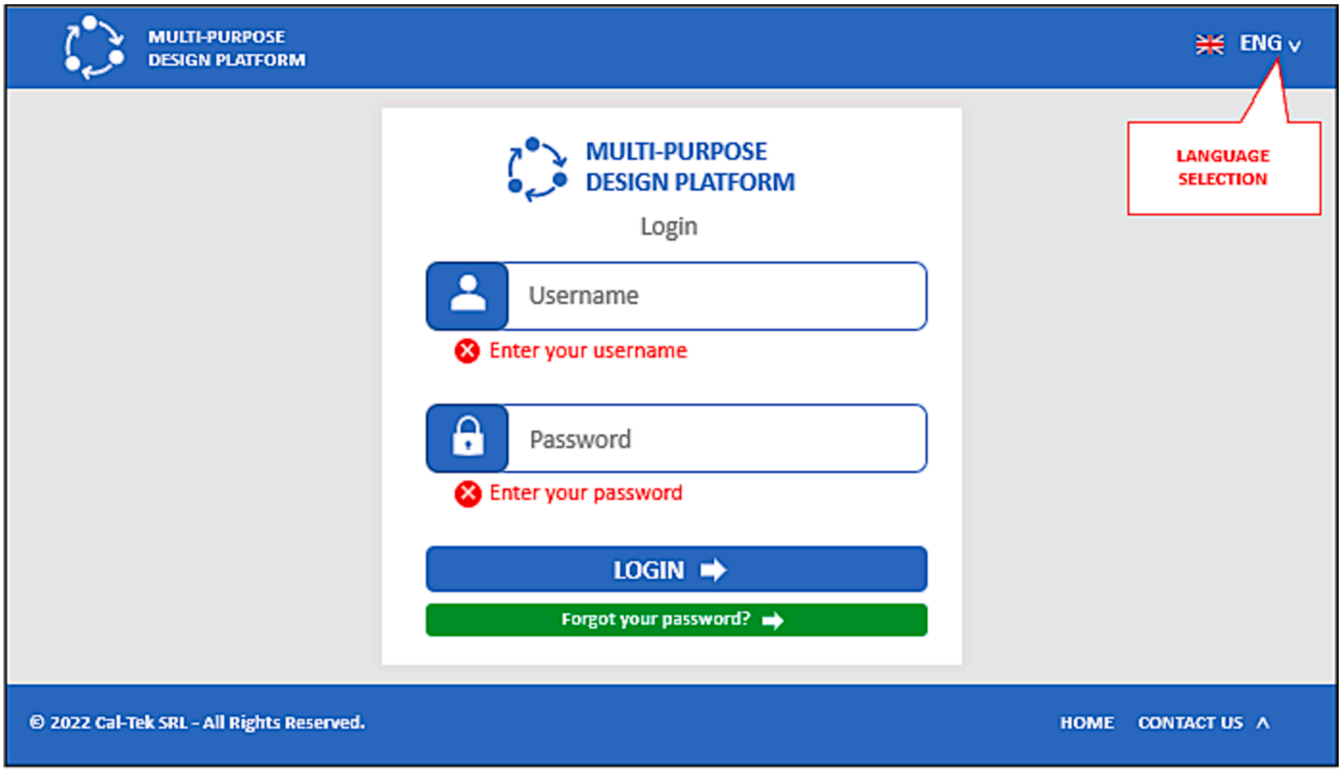
- Macro-operation 1A consists of the following production steps:
  1) *Step 1A.1*: shelves cut based on the designed dimensions starting from a raw material oak panel whose dimensions are 2 m (L) x 2 m (D). The SME currently plans to use a horizontal band saw to properly cut and dimension the shelves;
  2) Step *1A.2*: shelves planning to reach the shelves thickness (to be still finalized), starting from a raw material oak panel thickness of 25 mm. A planer machine is foreseen to perform this operation;
  3) *Step 1A.3*: shelves sanding to prepare them for the next drilling operation. The SME plans to use a double belt sander to carry out this production step;
  4) *Step 1A.4*: shelves drilling in order to make the holes necessary for the future assembly. One drilling machine is foreseen to perform this operation;
  5) *Step 1A.5*: shelves painting and drying; oak aesthetical characteristics are preserved by using wood stain instead of varnish. In terms of plant resources, SME plans to use one panting and drying machine.
- Macro-operation 2A consists of the following production steps:
  1) *Step 2A.1*: aluminum tubes cut based on the designed dimensions starting from raw material tubes 6 m in length. A circular saw is planned to be used to perform this operation;
  2) *Step 2A.2*: aluminum tubes bending operation in order to reach the X shape as shown in Fig. 5. A roller bender is currently planned to be used to perform this operation and a bending angle of 10° has to be set to avoid a possible bookcase structure future collapse;
  3) *Step 2A.3*: aluminum brackets welding to the tubes. Those brackets represent the supports where the final customers place the shelves and fix them to the bookcase structure by using standard wood screws. An automated welding machine is currently planned to be used to perform this operation;
  4) *Step 2A.4*: aluminum tubes painting and drying by using primers and paints suitable for aluminum processing. One painting and drying cabin is currently foreseen to perform this production step;
  5) *Step 2A.5*: assembly of the welded fit in aluminum by inserting two tube tops.
- Macro-operation 3A consists of the following production steps:
  1) *Step 3A.1*: preparation of packaging set 1 which includes the 5 oak shelves and the wood screws to fix them to the bookcase aluminum structure and decorative aluminum tubes;
  2) *Step 3A.2*: preparation of packaging set 2 which includes the bookcase feet (4 pieces) and the pivot being used for positioning the decorative aluminum tubes between the shelves as shown in Fig. 5.

Packaging set 1 and packaging set 2 are sent to the customers which have to complete by their own the final Bookcase assembly.

Case study objectives

The SME has set clear objectives that it aims to achieve by using the multi-purpose platform. The objectives are as follows:

1) The SME aims at using the SDT module to either confirm or optimize the production lines design in terms of currently planned resources,



MULTI-PURPOSE DESIGN PLATFORM

Login

Enter your username

Enter your password

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Fig. 6. Web App Login page.

such as the number of operators and machines to be used. The objective is to ensure that the production process is optimized for maximum efficiency and productivity. By using the SDT module, the SME can model and simulate the production process, analyze the factors that impact its efficiency, and identify areas where improvements can be made. This will help the SME to make data-driven decisions about the number of operators and machines required for each stage of the process, and to optimize the production process for maximum efficiency and profitability;

2) The SME aims at using the FEA module to conduct finite element analysis to properly design the bookcase from a structural point of view. This includes defining the bookcase shelves' thickness based on the maximum load it can hold and other parameters given as input by the SME. The objective is to ensure that the bookcase is structurally sound and can hold the intended load. By using the FEA module, the SME can accurately simulate and analyze the bookcase's structural behavior under various loading conditions and optimize its design accordingly;
3) The SME aims at using the NES module to define a nesting study that optimizes the production of a number of shelves full set from a single oak panel. The objective is to minimize material waste and optimize the production process to increase efficiency, reduce costs as well as to ensure the highest quality of the final product.

4.2. *Web application – User interface*

This section goes into the details of the Web-App being used by the end users to access and interact with the platform. The Web App is composed of a Front-End and a Back-End, which work together seamlessly to provide end users with a user-friendly and powerful platform. The Back-End of the web application has been developed to manage the platform's functionalities; among the others the main ones are described below:

- The Back-End allows that different types of end users (administrators and non-administrators) can configure and use the platform functionalities. To this end, the authors have defined the permissions and roles for different type of end users (i.e., manager, operator, product design engineer, FEA product engineer, etc.) by implementing authentication and authorization processes, and enforcing security policies to protect the application and its data;
- The Back-End ensures the management of users by administrators (such as creating, modifying, or deleting users). This includes implementation of user validation and verification processes and enforcing password policies;
- The Back-End ensures user registration, authentication and authorization processes. The user registration requires mandatory field such as name, surname, role (i.e., manager, operator, product design engineer, FEA product engineer, etc.) and password (with a minimum of 8 characters, including letters and numbers). Moreover, the OAuth protocol (Hardt, 2012) has been implemented to secure end users' login and logout;
- The Back-End provides differentiated access to the platform's functionalities and modules based on the user's role and permissions. This has been reached by implementing role-based access control, defining user groups and permissions, and enforcing restrictions on sensitive operations and data. For instance, the manager user group is granted to access to all platform modules, whereas the FEA product engineer is granted to access only the FEA module;
- The Back-End ensures the management of the personal area where end users can modify their information. User interface components have been implemented for managing user profiles, enforcing data validation and verification, and logging all user activities related to profile management.

As far as the Web App Front-End development is concerned, an ad-hoc and easy-to-use graphic user interfaces (GUI) has been developed. In Fig. 6, the login page is displayed. Here, the end users have the option to enter username and password and by clicking the "LOGIN" button,

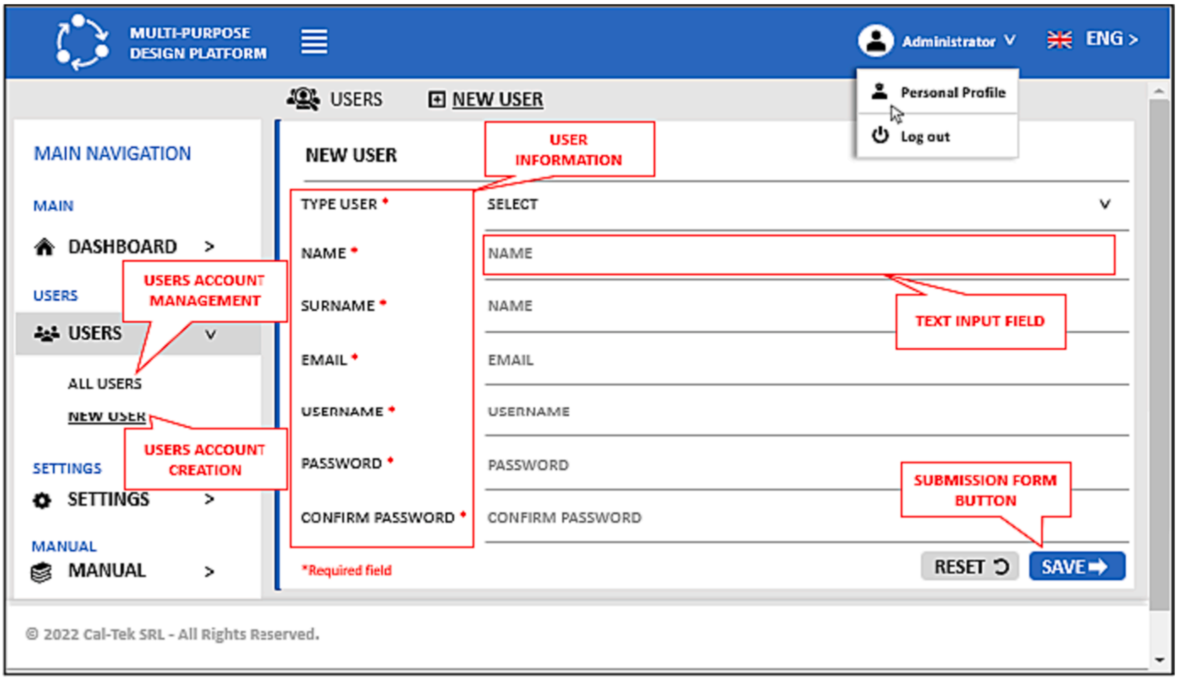


Fig. 7. Web App form for creating new user accounts.

Table 3
Maximum number of clicks to perform a What-If analysis.

DML	Clicks #							
	Main page selection	Input page selection	Design parameters selection	KPIs desiderata selection	Send button	Output page selection	KPIs visualization	Total
SDT Module	1	1	8	7	1	1	7	26
FEA Module	1	1	7	4	1	1	4	19
NES Module	1	1	15	0	1	1	4	23

they can gain access to the platform. Additionally, this page offers the "Forgot your password" button, which allows end users to initiate a password recovery process. End users will receive an email containing a link to reset their password. Fig. 7 depicts a form for creating new user accounts by the administrator. The form contains several fields for inputting user information, including a dropdown menu for selecting the user's role within the SME. The available roles may vary depending on the SME, but typical options include administrator, manager, operator, product design engineer, FEA product engineer, etc. Once the user's role has been selected, the administrator can input the user's personal details, such as their name, surname and email address, and define a unique username and password for the new account. The form also includes validation checks to ensure that the username and password meet the organization's security requirements. Upon submission of the form, the web application creates a new user account and adds it to the SME's user database. The administrator can then view and manage the user accounts, including editing or deleting them as needed. Basically, the web application provides a convenient and efficient way for administrators to create and manage user accounts within the SME, helping to ensure that the right people have the right level of access to the platform modules and therefore to the SME's resources and information.

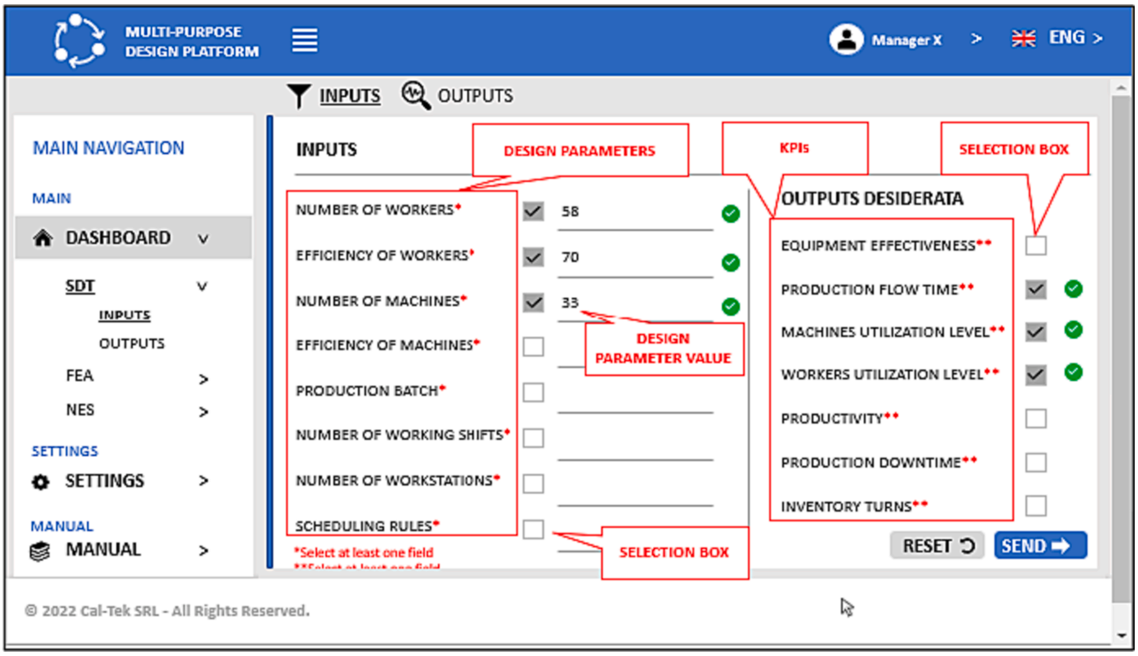
In addition, Table 3 calculates the maximum number of clicks needed to perform a what-if analysis related to the optimizations of either the production process (SDT module) or the product (FEA and NES modules). For each module, the following considerations are made regarding the number of clicks:

1) # Clicks required to select the module main page
2) # Clicks to access the module input section
3) # Clicks needed to select the design parameters
4) # Clicks for selecting the desired KPIs for analysis
5) # Clicks to send the data to the platform
6) # Clicks to access the module output section
7) # Clicks required to visualize the results of each analyzed KPI

It's important to note that these calculations represent the maximum number of clicks required, assuming the end user wishes to input all design parameters and analyze all available KPIs. For the NES module, no clicks are considered for KPI selection, as a nesting study requires evaluation of all KPIs, implemented within the platform, to be effective. Please be aware that these calculations do not include clicks for registering and logging into the platform or for entering values for the design parameters (essentially, the process of digitizing values).

5. Results

This section summarizes the most noteworthy results as outcome of the use of the multi-purpose platform. In particular, section 4.1 presents the main results achieved by using the SDT module, while section 4.2 and section 4.3 report respectively the outcomes of the FEA and NES



INPUTS

NUMBER OF WORKERS* ☑ 58
EFFICIENCY OF WORKERS* ☑ 70
NUMBER OF MACHINES* ☑ 33
EFFICIENCY OF MACHINES* ☐
PRODUCTION BATCH* ☐
NUMBER OF WORKING SHIFTS* ☐
NUMBER OF WORKSTATIONS* ☐
SCHEDULING RULES* ☐
*Select at least one field

OUTPUTS DESIDERATA

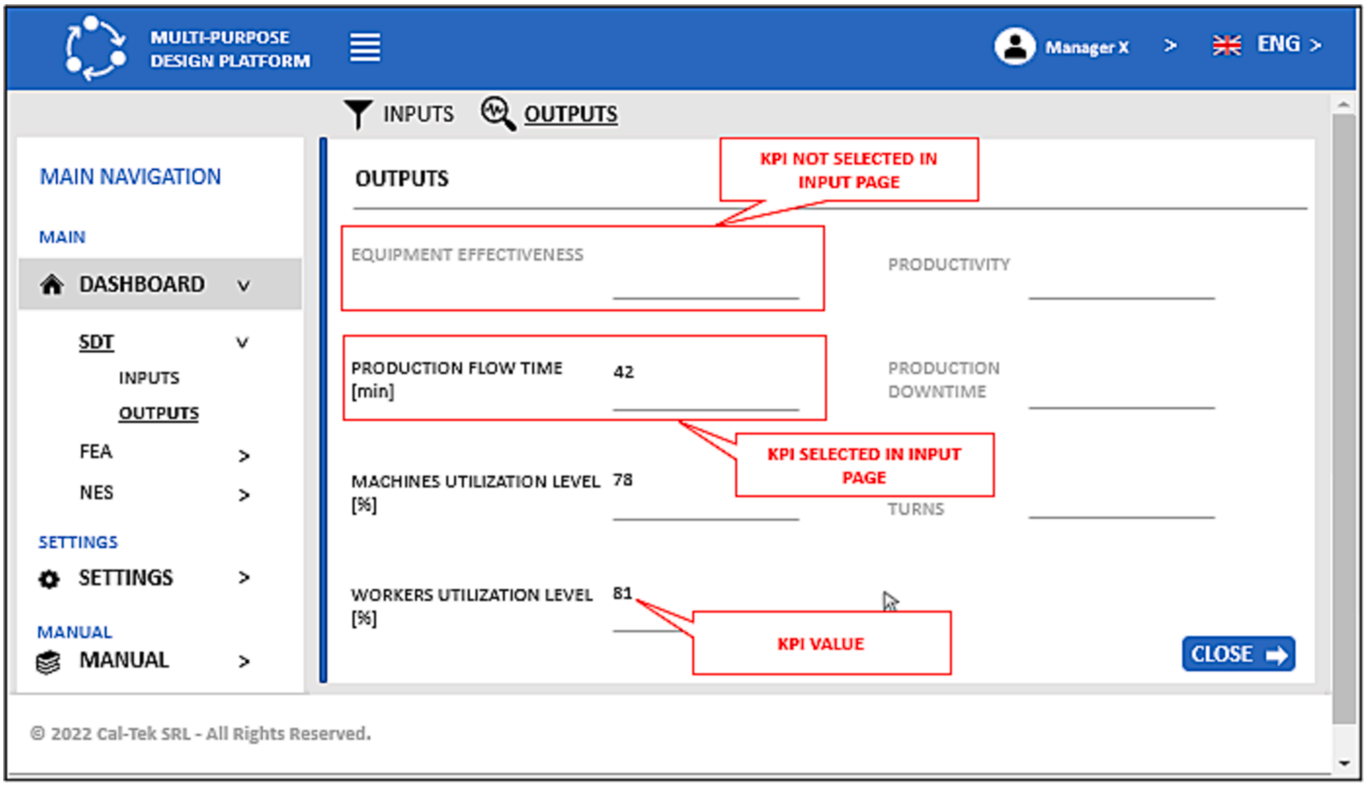
EQUIPMENT EFFECTIVENESS** ☐
PRODUCTION FLOW TIME** ☑
MACHINES UTILIZATION LEVEL** ☑
WORKERS UTILIZATION LEVEL** ☑
PRODUCTIVITY** ☐
PRODUCTION DOWNTIME** ☐
INVENTORY TURNS** ☐

Fig. 8. Web App SDT Module inputs page.

modules.

5.1. SDT Module: Production process design

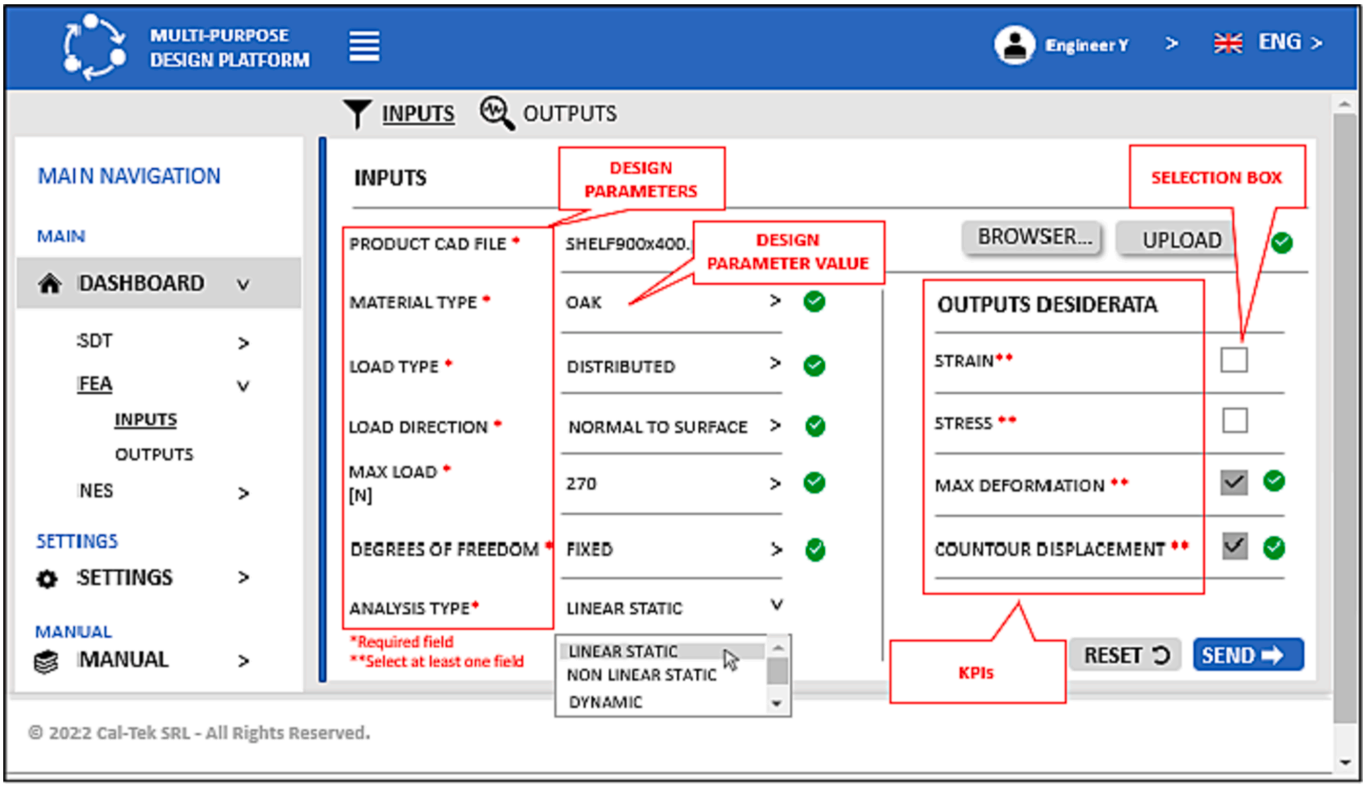
The SDT module deals with recreating the real production processes of the SME, through appropriate simulation models, with the aim of providing quantitative evaluations about the effects that different input parameters have on well-defined KPIs. In this context, Plant Simulation, a TECNOMATIX solution, has been integrated within the platform. As highlighted in the previous sections of the paper, the SME of the case study has already identified the production phases for the realization of the new product, however it is crucial to find the most suitable configuration. In this context, simulation represents a very powerful tool because it enables the execution of "offline" tests, where it is possible to eventually make errors without impacting the real system. Only after having verified, through appropriate what-if analyses, the goodness of



OUTPUTS

EQUIPMENT EFFECTIVENESS
PRODUCTION FLOW TIME [min] 42
MACHINES UTILIZATION LEVEL [%] 78
WORKERS UTILIZATION LEVEL [%] 81
PRODUCTIVITY
PRODUCTION DOWNTIME
TURNS

Fig. 9. Web App SDT Module outputs page.



INPUTS

PRODUCT CAD FILE *	SHELF900x400.
MATERIAL TYPE *	OAK ✓
LOAD TYPE *	DISTRIBUTED ✓
LOAD DIRECTION *	NORMAL TO SURFACE ✓
MAX LOAD * [N]	270 ✓
DEGREES OF FREEDOM *	FIXED ✓
ANALYSIS TYPE*	LINEAR STATIC

*Required field
**Select at least one field

OUTPUTS DESIDERATA

STRAIN**	☐
STRESS **	☐
MAX DEFORMATION **	☑ ✓
COUNTOUR DISPLACEMENT **	☑ ✓

Fig. 10. Web App FEA module inputs page.

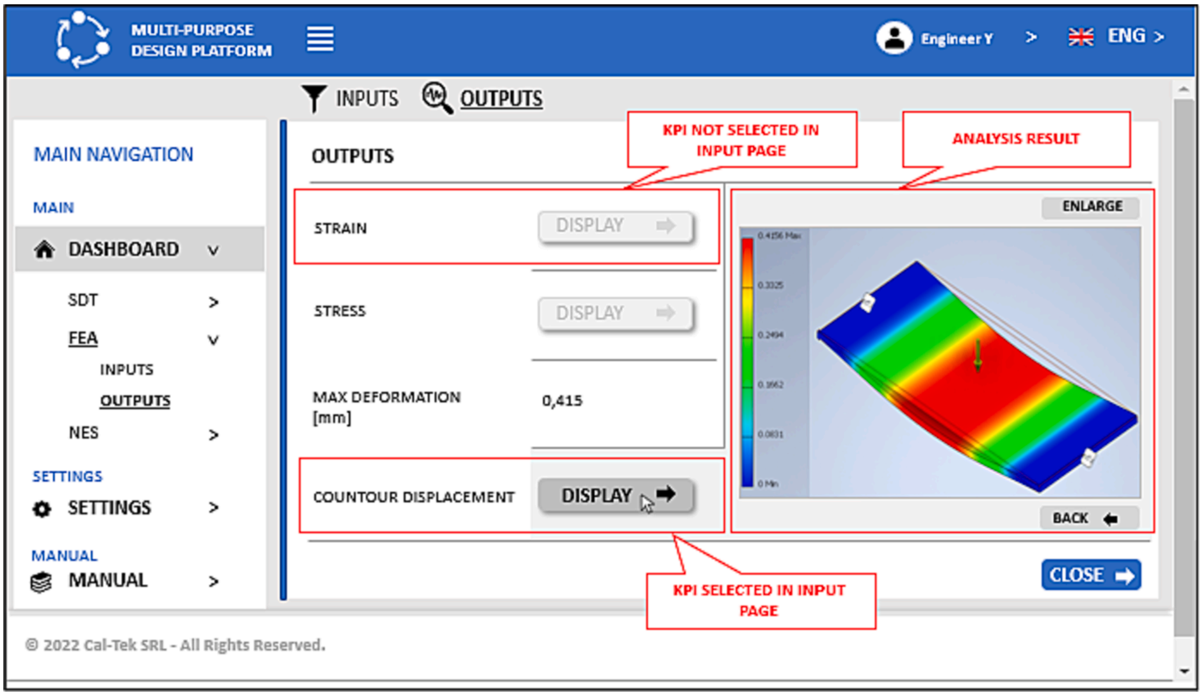
each solution, it is possible to proceed with the actual implementation on the real system.

The construction of the simulation model, which represents the real production system, is out of the scope of this paper. In fact, the SDT Module has the only purpose of guiding a user, even one who is inexperienced from the point of view of digital technologies, in choosing the most suitable input parameters to achieve specific KPIs. However, to improve the reader's understanding, it is relevant to say that the entire production process has been divided into 3 simulation frames: manufacturing, assembly, packaging. As it is possible to see in the next figures, the Web App provides a very simple and intuitive interface. Fig. 8 illustrates the end user's selection of inputs necessary to conduct a what-if analysis. The page presents a list of all available design parameters on the left side, and on the right side, it lists the desired output criteria for the analysis. Regarding input parameters, end users can select each one by simply checking the box next to the design parameter and subsequently assigning the desired values. As for output selection, end users on this page can choose only the specific outputs for which they want to run the analysis. Once the input information has been provided, end users can initiate the analysis by clicking the "SEND" button. Plant Simulation begins processing, and within few seconds, the results are returned to the end user in an intuitive and usable way, as shown in Fig. 9. In the Web App's SDT module outputs page, the list of outputs is presented. This page specifically showcases the values of all the outputs that were previously selected on the input page. However, for outputs that were not selected, no values are displayed, and they appear in a light grey color to make them less prominent and easily distinguishable.

After running and analyzing various simulation scenarios, the SME was able to identify the best configuration of input parameters, aimed at maximizing productivity and profitability. It is out of the scope of the paper to list the results of all simulation scenarios, which supported the SME in this decision-making. However, for the convenience of the reader some insights are listed below. Through the SDT Module, the SME discovered that the number of machines is the input factor with the most significant impact on flow time, especially in the manufacturing workplace which is less manual than assembly and packaging ones. This analysis was important in determining the number of duplicate machines to be placed in parallel. The number of workers to be employed for the manufacturing of the new product and their level of specialization (i.e., worker's efficiency) were identified through a cost-benefit analysis: costs, i.e., salary to be paid to each of them; benefits, i.e., reduction of the flow time and increase in the production capacity of the plant due to the use of each additional human resource. Many other input parameters were determined through a careful analysis of the above-mentioned simulation scenarios.

5.2. FEA Module: Structural design optimization of the bookcase shelves

This section provides a detailed description of the FEA Module application in order to determine the optimized thickness of bookcase shelves. The SME has set two key requirements for the bookcase shelves: uniform thickness across all shelves and a maximum deformation of 0.5 mm for each shelf when loaded. Uniform thickness across all shelves ensures aesthetically consistent among the shelves. The maximum deformation of 0.5 mm when loaded is a critical factor in ensuring that the shelves do not sag or bend beyond an acceptable limit, which could result in damage to the books or the overall structure of the bookcase. In order to ensure structural integrity, the SME decided to determine the thickness of the shelves on the worst-case scenario, defined the longest shelf, which is expected to experience the greatest stress and deformation under load. To use this module, the SME has entered relevant data through the web application, which has been then used as input from the FEA module. Once the analysis has been completed, the FEA module provided back the SME with specific KPIs such as maximum deformation and contour displacement, whose values determined whether further evaluation was required. The SME inputted data on the longest shelf (900 mm) cad model, max load (270 N), analysis type (linear static),



OUTPUTS

STRAIN DISPLAY

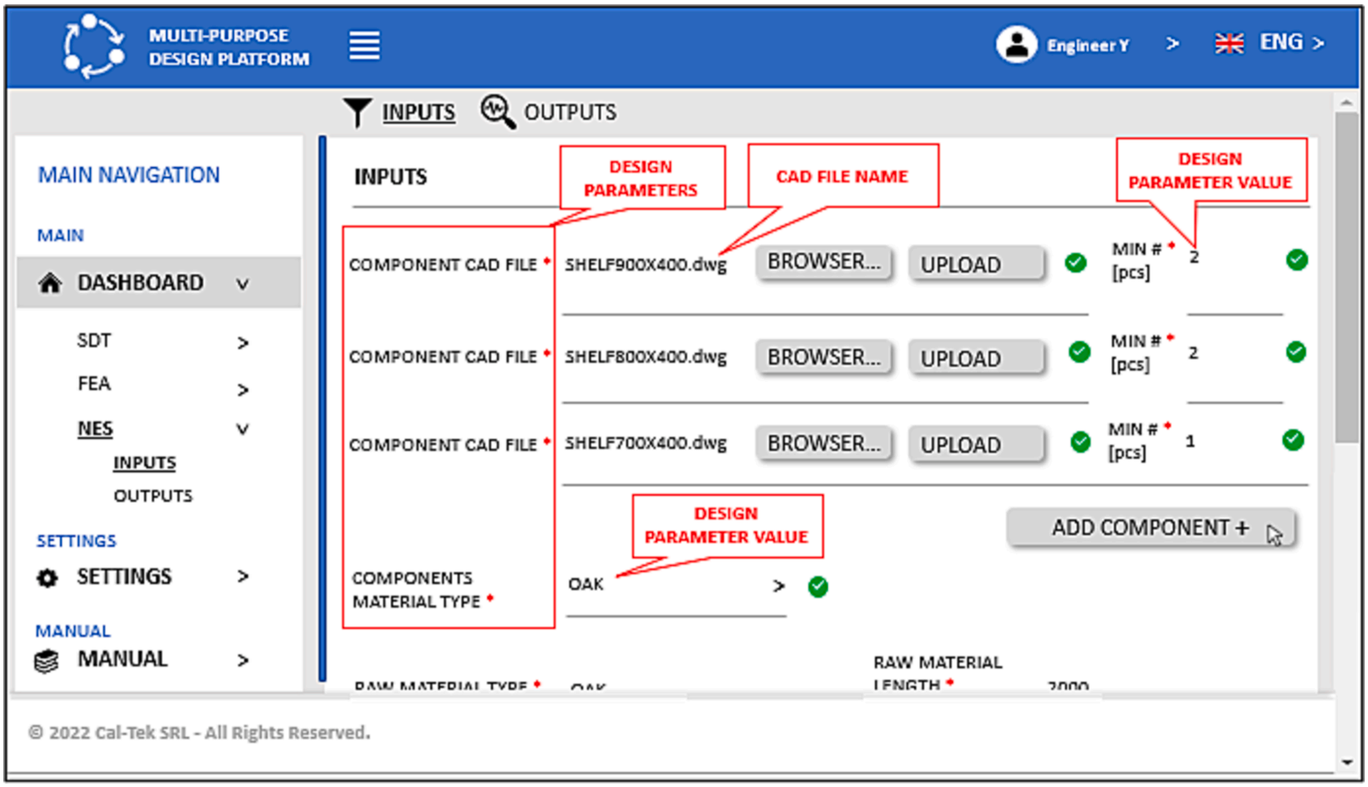
STRESS DISPLAY

MAX DEFORMATION [mm] 0,415

COUNTOUR DISPLACEMENT DISPLAY

Fig. 11. Web App FEA module outputs page.

material (oak), load type (distributed), load direction (normal to surface), and shelf degrees of freedom (none). The KPIs selected for calculation were the max deformation value and contour displacement. Upon running the analysis with a shelf thickness of 10 mm (value as per CAD model dimensions), the FEA module displayed a deformation level higher than the 0.5 mm requirement. Therefore, the analysis was repeated with a shelf thickness of 20 mm (through an updated of the Cad model), while all other parameters remained unchanged. The analysis resulted in a maximum deformation of 0.415 mm, which is below the specified deformation limit. In conclusion, the first run of the analysis did not meet the SME's requirements, however, the second run with a shelf thickness of 20 mm resulted in a deformation value which satisfied the requirements. Based on these results, the SME could make an informed decision on the appropriate thickness of the bookcase shelves.



INPUTS

COMPONENT CAD FILE * SHELF900X400.dwg MIN # * [pcs] 2

COMPONENT CAD FILE * SHELF800X400.dwg MIN # * [pcs] 2

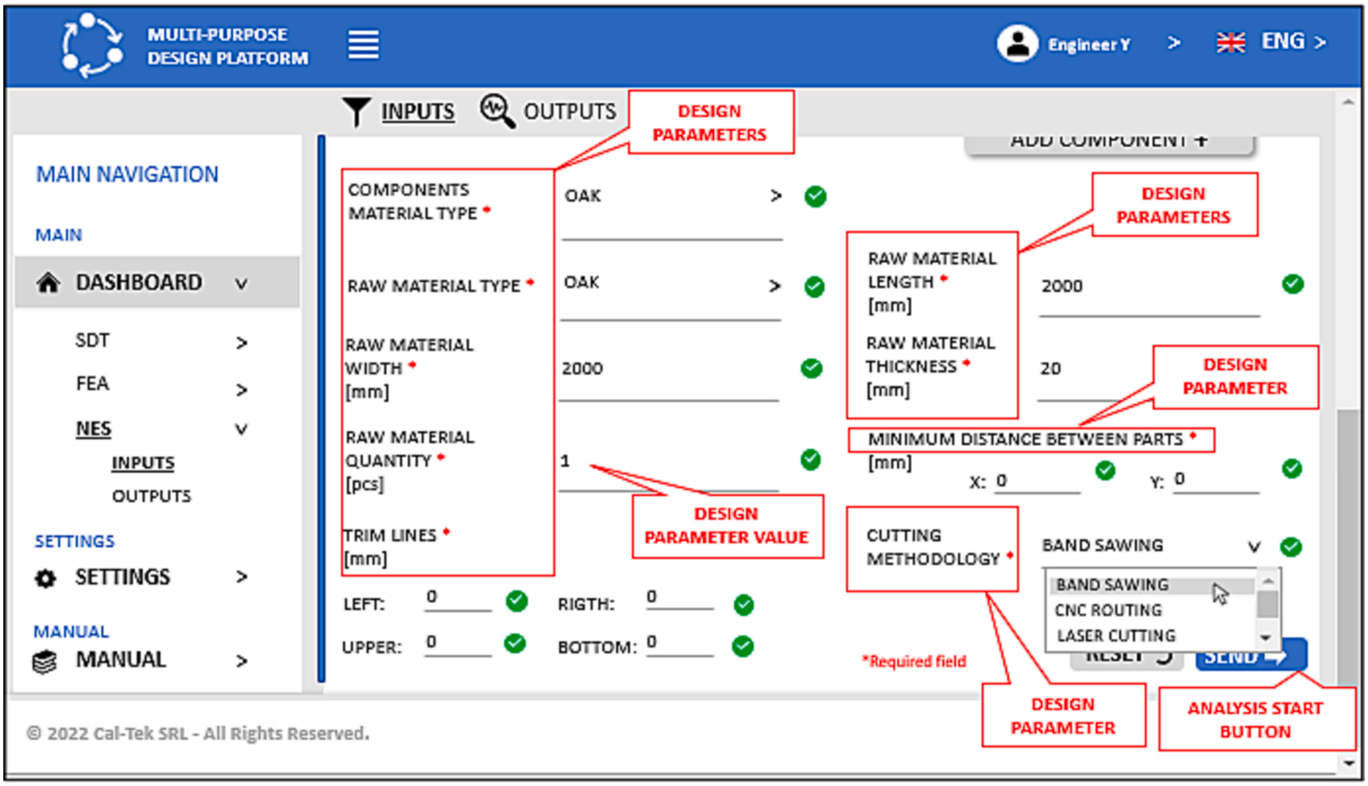
COMPONENT CAD FILE * SHELF700X400.dwg MIN # * [pcs] 1

COMPONENTS MATERIAL TYPE * OAK

RAW MATERIAL TYPE * OAK

RAW MATERIAL LENGTH * 2000

Fig. 12. Web App NES module inputs page – part 1.



COMPONENTS MATERIAL TYPE *: OAK >

RAW MATERIAL TYPE *: OAK >

RAW MATERIAL WIDTH * [mm]: 2000

RAW MATERIAL QUANTITY * [pcs]: 1

TRIM LINES * [mm]

LEFT: 0 RIGTH: 0

UPPER: 0 BOTTOM: 0

RAW MATERIAL LENGTH * [mm]: 2000

RAW MATERIAL THICKNESS * [mm]: 20

MINIMUM DISTANCE BETWEEN PARTS * [mm] X: 0 Y: 0

CUTTING METHODOLOGY *: BAND SAWING v

BAND SAWING
CNC ROUTING
LASER CUTTING

*Required field

DESIGN PARAMETERS

DESIGN PARAMETERS

DESIGN PARAMETER

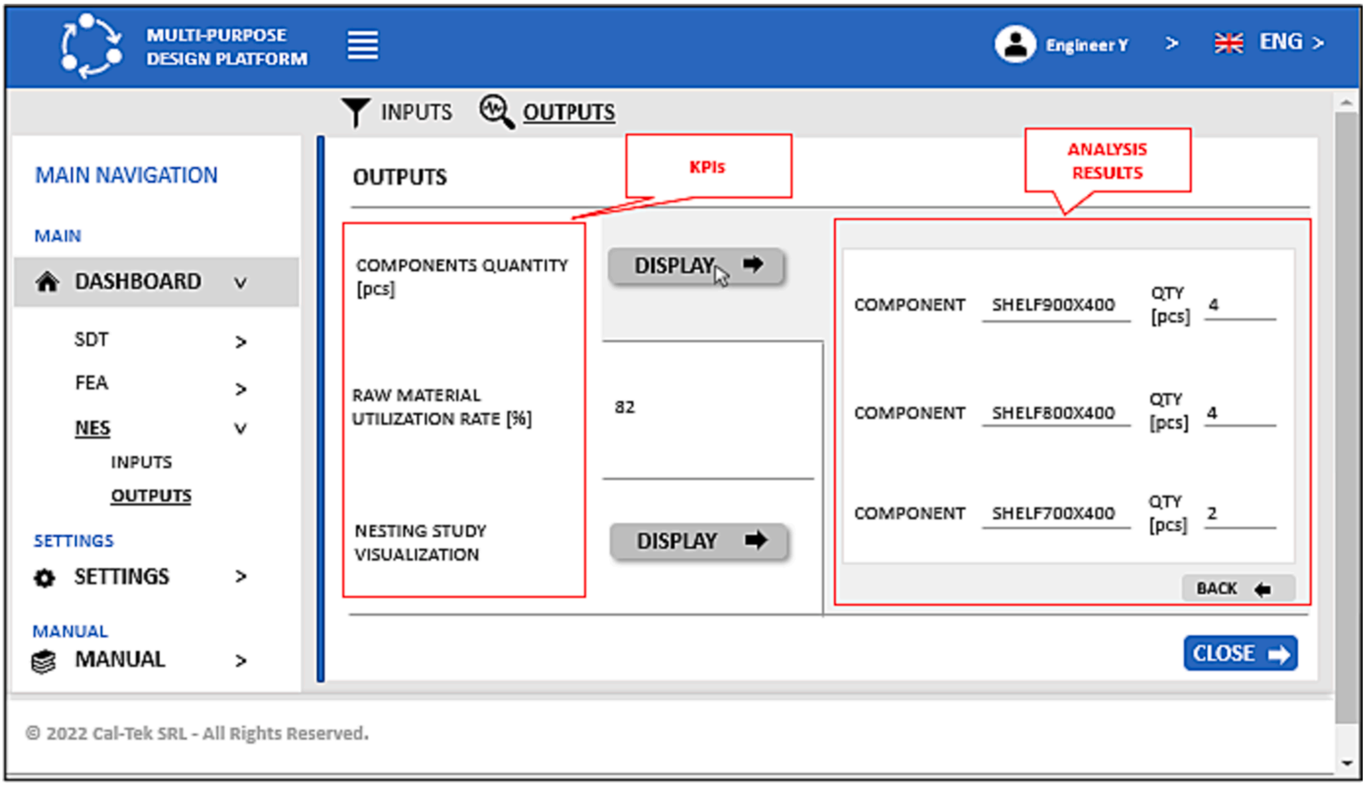
DESIGN PARAMETER VALUE

DESIGN PARAMETER

ANALYSIS START BUTTON

Fig. 13. Web App NES module inputs page – part 2.

Figs. 10 and 11 display the Web App pages containing the input data and output results, respectively, for the final configuration of the shelf with a thickness of 20 mm, which was the result of the second attempt carried out by the SME. From the FEA module inputs page, end users have the capability to enter values for all design parameters, along with the option to upload the CAD model of the product to be analyzed. This page



OUTPUTS

COMPONENTS QUANTITY [pcs]

RAW MATERIAL UTILIZATION RATE [%]: 82

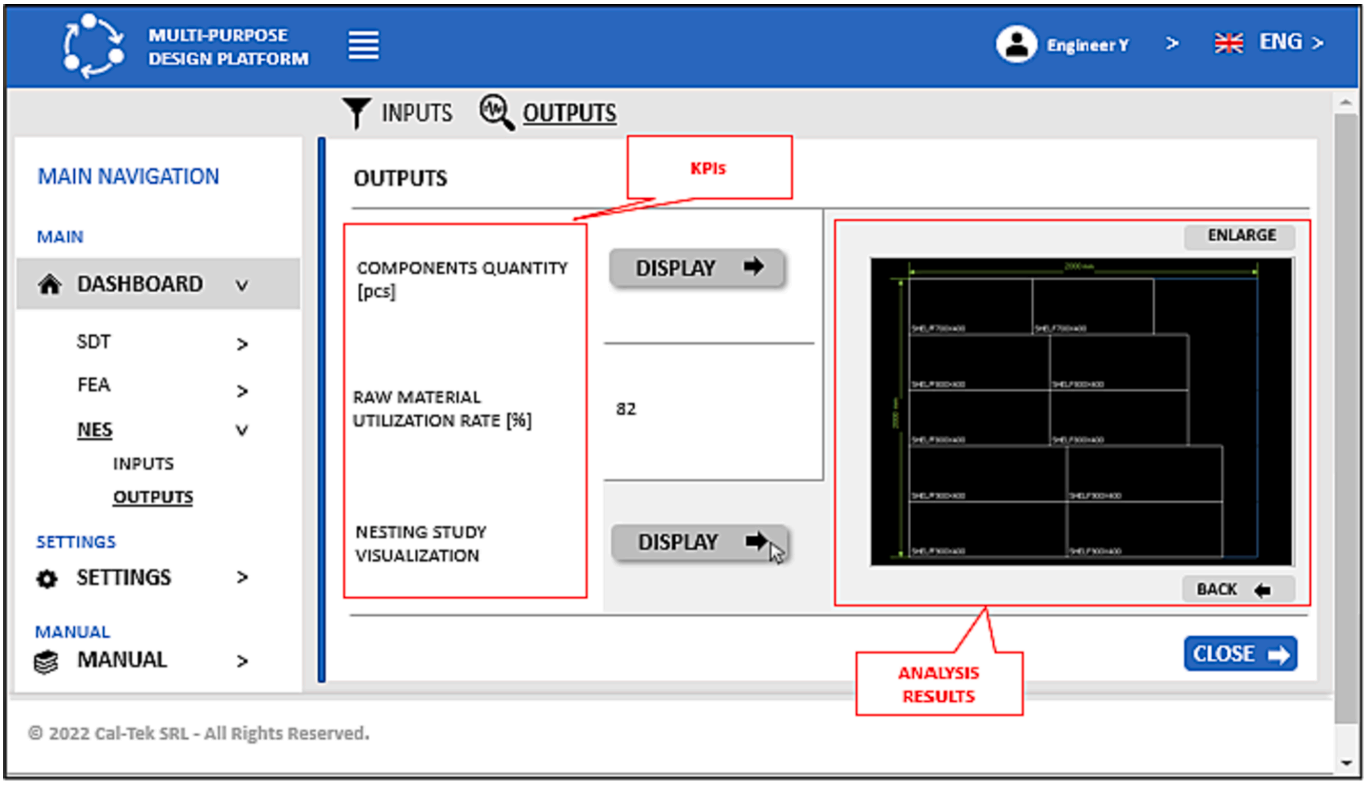
NESTING STUDY VISUALIZATION

COMPONENT	SHELF900X400	QTY [pcs]	4
COMPONENT	SHELF800X400	QTY [pcs]	4
COMPONENT	SHELF700X400	QTY [pcs]	2

KPIs

ANALYSIS RESULTS

Fig. 14. Web App NES module outputs page – part 1.



OUTPUTS

COMPONENTS QUANTITY [pcs]	DISPLAY
RAW MATERIAL UTILIZATION RATE [%]	82
NESTING STUDY VISUALIZATION	DISPLAY

Fig. 15. Web App NES module outputs page – part 2.

provides a “BROWSER” button that allows end users to select the CAD file from their saved location. After selecting the file, end users can initiate the upload process by clicking the “UPLOAD” button. Additionally, end users can choose the desired outputs (KPIs) for the analysis from the list of the ones implemented within the module. When it comes to the FEA module outputs page, the end users can view the list of KPIs implemented within the module. However, it’s important to note that results from the analysis are available for visualization only for those KPIs that were selected during the input process.

5.3. NES Module: Bookcase shelves nesting study

This section provides a detailed description of the NES Module application, which is used by the SME to optimize the cut of a number of shelves from a single oak panel. The SME has set two key requirements: maximizing the number of full set of shelves that can be cut from a single oak panel and minimizing waste. The NES module has been designed to meet these requirements by providing a nesting study that determines the most efficient way to cut the shelves from the oak panel, minimizing the amount of waste generated. As done for the FEA module application, the SME has entered the relevant data through the web application. The input data includes the dimensions of the oak panel raw material, which is 2 m in length and 2 m in depth and the type of material, which is oak. Moreover, the SME has also provided the CAD model of each shelf type to be cut, which in this case consists of 2 sub-components of dimensions 900 mm x 400 mm, 1 sub-component of dimensions 700 mm x 400 mm, and 2 sub-components of dimensions 800 mm x 400 mm. The minimum number for each sub-component to be cut is also specified (two pieces each for shelves 900 mm and 800 mm in length and one pieces for the shelf 700 mm in length) as well as the minimum distance between subcomponents (0 mm in X and Y directions) and the cutting methodology (band sawing). The left, right, bottom and upper trim lines, which define the area to be trimmed, are set to zero in order to use the full surface of the raw material panel. Once the input data is entered through the web application, the NES module analyses the data and provides a 2D visualization of the nesting study as output. The output shows the optimized placement of the sub-components on the oak panel, with each sub-component represented by a rectangular shape. In addition, the NES module has also provided the SME with specific KPIs, such as the total number of sub-components that can be cut and the raw material panel utilization rate (in %). Fig. 12 and Fig. 13 display the web application page containing the input data for the NES module, while Fig. 14 and Fig. 15 show the output of the NES module, which is the number pieces to be cut for each component, the raw material utilization rate and the 2D visualization of the nesting study. During the input process, end users can provide input data, including CAD files related to the components for which nesting analysis needs to be performed. End users have the option to upload CAD files using the “BROWSER” and “UPLOAD” buttons. Additionally, they can choose to add more components by clicking the “ADD COMPONENT +” button, which creates a new input section for uploading another CAD file.

Once all input data have been entered, end users can initiate the nesting analysis by clicking the “SEND” button. In the NES module outputs page, the results of the nesting study are presented, including information such as components quantity, raw material utilization rate, and visualization of the nesting study. Display buttons within the page enable end users to visualize the analysis results.

6. Conclusions

Based on the research activities carried out, this study has developed a multi-purpose platform that can be used by SMEs as an easy-to-use support tool to run what-if analysis in order to optimize the design of production processes and products. The proposed platform, based on a layered infrastructure, combines different modules and fulfils the requirements of interoperability, accessibility, and usability. The platform’s layered structure was described, along with its Decision-Making Layer, Data Exchange Layer, and User Management Layer, each consisting of specific modules. The authors successfully integrated Plant Simulation, Autodesk Inventor Nastran, and Autodesk Inventor Nesting

Table A1
Multipurpose platform data models.

Platform Module	Data Model	Data attribute name	Data attribute type	Data attribute description
SDT	inputSDT (Design parameters)	workersNumber	Int	Number of workers employed in the production line
		workersEfficiency	Double	Efficiency of the workers employed in the production line (i.e., beginner, expert, etc.)
		machinesNumber	Int	Number of machines used in the production line
		machineEfficiency	Double	Efficiency of the machines used in the production line
		productionBatch	Int	Number of identical products that goes through the production line together
		workingShiftNumber	Int	Number of working shift per day
		workstationsNumber	Int	Number of workstations within the production line
		schedulingRules	String	Rules of scheduling to supply the production line (FIFO, LIFO, etc.)
	outputSDT (KPIs)	overallEquipmentEffectiveness	Double	Percentage of time in which a production line produces good quality products during the scheduled time
		productionFlowTime	Double	Time to manufacture a product from when production starts until it finishes
		machinesUtilizationLevel	Double	Average utilization level of the production line machines
		workerUtilizationLevel	Double	Average utilization level of the production line workers
		productivity	Int	Number of products manufactured in a defined time period
		productionDowntime	Int	Time period when the manufacturing process is on hold and no products are produced.
		inventoryTurns	Int	Inventory level within the production system
FEA	inputFEA (Design parameters)	cadModel	String (URL path)	Product 3D CAD model
		analysisType	String	Type of structural analysis to be run
		outputsStrain	Boolean	Output information that end-user wants to visualize
		outputsStress	Boolean	
		outputsmaxDeformation	Boolean	
		outputsCountourDisplacement	Boolean	
		ComponentMaterial	String	Material component types
		Load	Int	Max load applied to the product
		LoadType	String	Type of load applied to the product
		loadDirection	String	Direction of the Load applied to the product
		degreesOfFreedom	String	Product degrees of freedom
	outputFEA (KPIs)	strain	String	Relative change in length caused by a deforming force
		stress	String	Deforming force per unit area of the object
		contourDisplacement	String	Contour displacement due to the applied load
		maxDeformation	Double	It measures product max deformation due to the applied load
NES	inputNES (Design parameters)	nestingComponentCadModel	String (URL path)	Nesting Component 3D CAD model
		nestingComponentMaterialType	String	Nesting Component Material Type
		rawMaterialPanelType	String	Raw material panel types
		rawMaterialPanelLength	Double	Raw material panel length
		rawMaterialPanelWidth	Double	Raw material panel width
		rawMaterialPanelThickness	Double	Raw material panel thickness
		rawMaterialPanelQuantity	Int	Number of available raw material panel
		minimumDistanceBetweenPartsX	Double	Distance between parts to be cut in X direction
		minimumDistanceBetweenPartsY	Double	Distance between parts to be cut in Y direction
		cuttingTechnology	String	Technology to be used to cut the parts
		leftTrimLine	Double	Nesting area
		rigthTrimLine	Double	
		bottomTrimLine	Double	
		upperTrimLine	Double	
		minNumber	Int	Min number of components which need to be cut
	outputNES (KPIs)	nestingVisualization	String	2D nesting results visualization
		jobQuantity	Int	Number components which need to be cut
		rawMaterialPanelnumber	Int	Number of used raw material panels
		nestingEfficiency	Double	Raw material panel utilization level

software into the platform, allowing SMEs to simulate production processes, to run finite element analysis, and to optimize raw material utilization. The interoperability and data exchange were ensured through the adoption of FIWARE, an open-source framework for IoT platforms, which enabled the harmonized representation of data formats and semantics among different applications and software within the platform. The research work concludes also with an application of the multi-purpose platform conducted by a SME, located in Calabria (Italy) and operating in the furniture sector. The SME in question set clear objectives to achieve optimal design and production of a new bookcase, with the aim of minimizing material waste, increasing efficiency, and maximizing profitability. The SDT module was used to model and simulate the production process, identifying areas where improvements could be made and optimizing the process for maximum efficiency and productivity. Additionally, the SME utilized the platform's FEA module to conduct structural analysis of the bookcase design, ensuring that the bookcase shelves' thickness was optimized to withstand the intended load. Finally, the NES module was utilized to optimize the production of shelves from a single oak panel, resulting in reduced material waste and increased efficiency. This case study highlights the value of utilizing a multi-purpose platform as an accessible and user-friendly tool to support SMEs in taking data-driven decisions that improve their products and production processes design, resulting in increased efficiency, reduced costs, and improved profitability. In addition to the platform's current capabilities, the modular structure of the platform enables the easy integration of new modules, providing further potential benefits for SMEs. For example, the platform could be expanded to include quality control and supply chain management modules, allowing SMEs to streamline their production processes even further and increase their competitiveness in the market. It's important to note that these activities will require further research efforts; specifically, the selection of the software for integration within the platform along with the identification of the modules design parameters and KPIs needs to be further investigated. Another possible future development concerns the integration of mathematical and statistical tools (e.g., Minitab (Alin, 2010)) within the SDT module, with the aim of directly providing the user with easily interpretable graphs and improving decision-making. Furthermore, as additional potential area of improvement, it's worth noting that although, theoretically, the direct and automatic DML inter-module (SDT/FEA/NES) data exchange is feasible, thanks to the integration of FIWARE, this feature has not yet been implemented. Therefore, to further enhance the platform capabilities, additional research efforts are definitely needed towards enabling direct and automatic data exchange among the modules.

CRediT authorship contribution statement

Antonio Cimino: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Maria Grazia Gnoni:** Validation, Investigation, Writing – original draft, Writing – review & editing. **Francesco Longo:** Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Vittorio Solina:** Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix

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