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Integrating Materials and Manufacturing Innovation

ISSN 2193-9764

Integr Mater Manuf Innov
DOI 10.1007/s40192-019-00139-2

Integrating Materials and Manufacturing Innovation
https://doi.org/10.1007/s40192-019-00139-2

THEMATIC SECTION: 5TH WORLD CONGRESS ON INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING

Cloud-Based Materials and Product Realization—Fostering ICME Via Industry 4.0

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Received: 2 February 2019 / Accepted: 30 April 2019

Abstract

Facilitating integrated computational materials engineering (ICME) in the digitized world necessitates facilitating a network of participants (material scientists, systems designers, software developers, service customers) to share material/product/manufacturing process/market data, information, knowledge, and resources instantly and collaborate so as to facilitate a cost-effective co-creation of value supporting open innovation. Industry 4.0, a transformative industrial revolution with its new product development paradigms like cloud-based design and cloud-based manufacturing, supports this need. In this paper, we present the architecture and functionalities of a cloud-based computational platform to facilitate mass collaboration and open innovation thereby supporting integrated material and product realization to institutionalize ICME in industry. We illustrate the efficacy of the proposed cloud-based platform using a hot rolling example problem to produce a steel rod. Using this example, we illustrate the utility of the cloud-based platform in
seamless, yet controllable, information, knowledge, and resource sharing thereby supporting the integrated design of materials, products, and manufacturing processes.

Keywords Cloud-based design for ICME · Collaboration and sharing in design

Frame of Reference

The integrated computational materials engineering (ICME) [1, 2] community aims at exploiting the advancements in computational modeling tools and simulations supported by knowledge-based engineering tools for realizing the system-based, integrated design exploration of materials, products, and manufacturing processes meeting end customer requirements. In order to foster ICME in the current world and realize its full potentials, there is a need to facilitate a network of participants, which includes material scientists, system designers, software developers, end service customers to come together and share material/product/manufacturing process/market data, information, knowledge, and resources instantly, and collaborate so as to facilitate a cost-effective co-creation of value supporting open innovation. This necessitates the creation of computational platforms that enable seamless, yet controllable, information, knowledge, and resource sharing supporting the integrated design of materials, products, and manufacturing processes. The domain-independent platform thus developed should support model development; model and simulation software integration; problem formulation; design and solution space exploration and visualization; data, information, and knowledge management (capture, store, retrieve); and knowledge-based design guidance so as to provide design decision support for materials and product designers who might be collaborating from different parts of the world. The platform from the context of ICME should support designers in coming with smart and intelligent manufacturing procedures for product realization with reduced design and production time in developing robust products. Industry 4.0, a transformative industrial revolution with its new product development paradigms like cloud-based design and cloud-based manufacturing,

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supports this need. As discussed by Thames and Schaefer [3], Industry 4.0 and its associated technologies such as cloud-based design and manufacturing systems, the Internet of Things (IoT), the Industrial Internet of Things, and Social-Product Development are driven by technologies and innovations that are disruptive leading to massive creation of value to those involved in the market sectors. This new revolution is a result of the convergence of industrial systems with advanced computing technologies, sensors, and ubiquitous communication systems [3]. In this paper, we address how the technologies associated with Industry 4.0, especially cloud-based design, can change the way we realize materials and products and the way they are designed.

One major change that has happened with these new technologies is the power shift from the hierarchical business models that used to exist in industry to cooperative collaboration networks with a mindset of sharing to gain. This is true in the case of design also. Using traditional product realization design paradigms like the Pahl and Beitz [4] systematic design approach and Suh's Axiomatic Design [5], a designer is able to describe product development as a series of core transformations where information is shared sequentially. However, these traditional design paradigms are not competent to address the changing needs and technologies associated with product realization as required for ICME. "Neither Pahl and Beitz design method nor Suh's Axiomatic Design offers a framework that facilitates seamless information, knowledge and resource sharing, or aids participants of global value co-creation networks in identifying potential collaboration partners or resource providers," [3, 6, 7].

The need therefore identified in this paper from the ICME perspective is for a platform that facilitates a network of participants involved in materials and product realization to share information, knowledge, and design/manufacturing resources so as to facilitate co-creation of value in a more cost-effective manner. Thus, traditional product development methods need to be updated and bridged to the new developments happening in the globalized world like cloud-based design and manufacturing; the foundations for which is provided in [7].

The paper is organized as follows. In "Core Competencies Needed for Product Realization," we identify the core competencies needed for a designer using the platform developed for implementing an ICME-driven product realization in industry. In "Proposed Cloud-Based Platform for Decision Support in the Design of Engineering Systems (CB-PDSIDES)," we discuss platform PDSIDES and propose the cloud-based platform CB-PDSIDES. In "Core Functionalities Offered by CB-PDSIDES in ICME Context," the core functionalities offered by CB-PDSIDES in ICME context is discussed. The demonstration of the key core functionalities using an industry-inspired problem is carried out in "Cloud-Based Design of Materials and Products—Design of a Hot Rolled Steel Rod Example." We end the paper with "Closing Remarks."

Core Competencies Needed for Product Realization

Model-based realization of complex systems necessitates designers to deal with models that are typically incomplete, inaccurate, and not of equal fidelity. One focus of ICME-based research in industry is in mitigating the uncertainty in models by seeking "perfect" models, collecting more data, and developing improved methods to model, calculate, and quantify uncertainty through expensive computations. There are several challenges associated with this, as highlighted by McDowell [8]. The alternative to this is to focus on managing the uncertainty by designing the material/product systems to be insensitive to the sources of uncertainty without reducing or eliminating them—also defined as robust concept exploration [9], which is our focus in this paper. Successful institutionalization of ICME in industry, however, requires the development of platforms that can enable human designers to carry out materials and product design using simulation models by providing design decision support.

The core competencies needed for a designer using the platform developed for implementing an ICME-driven product realization in industry are identified as follows:

1. Capability to integrate models and simulation tools spanning different processes and length scales (typically defined as vertical and horizontal integrations in ICME context);
2. Capability to define computational workflows involving decision-making, spanning multiple activities and users; define modular, reusable sub-workflows for specific processes;
3. Capability to connect to external databases on materials, products, and processes;
4. Capability to provide knowledge-guided assistance to different types of users in design-related decision-making;
5. Capability to carry out collaborative, multidisciplinary design and privacy control;
6. Capability to manage complexity (reduced cost of computation via surrogate models/meta models);
7. Capability to explore and visualize the design and solution space;
8. Capability to carry out dynamic and cost-efficient reconfiguration and integration of design decision templates to

explore different robust design strategies (meta-design to deliver robust products).

Proposed Cloud-Based Platform for Decision Support in the Design of Engineering Systems

Platform for Decision Support in the Design of Engineering Systems

Mistree and co-authors [10] define design as the conversion of information that characterizes the needs and requirements for a product into knowledge about the product. The underlying philosophy in the definition of design by Mistree and co-authors [10] is that the designer starting with the functional requirements that is desired (the goal that designer wishes to achieve) should be able to work backwards to explore effective design solutions. This philosophy is adopted in this paper for design—as a goal-oriented activity. As noted by Gero [11], the designing involves transforming requirements—generally termed *functions*—into design descriptions. *Decision-based design* [10, 12] is a term coined to emphasize a different perspective to develop methods for design. The principal role of a human designer in decision-based design (DBD) is to make decisions given the information available. From an engineering perspective, decisions exclusively deal with allocation of resources in some form, usually as capital expenditures. Thus, the definition of a decision here is as "an irrevocable allocation of resources" [13]. We believe that there are two types of decisions that a human designer can make: selection and compromise decisions. A complex design can be represented by modeling a workflow of compromise and selection decisions, achieved using PDSIDES.

PDSIDES [14] is a "Knowledge-Based" Platform for Decision Support in the Design of Engineering Systems (PDSIDES) that is anchored in modeling decision-related knowledge with templates using ontologies to facilitate execution and reuse. The two primary constructs required for the realization of decisions within PDSIDES are [14] (1) decision support problem (DSP) construct and (2) ontology. Three types of platform users are defined according to the amount of knowledge they have for operating the decision template, namely, template creators, template editors, and template implementers. Template creators are domain experts and responsible for creating decision templates for original design, which requires the greatest novelty. Template editors are senior designers who have sufficient knowledge and experience in a specific domain and are responsible for editing (or tailoring) existing decision templates in adaptive design; this requires the original templates to be adapted for new applications. Template implementers are designers who have basic knowledge and typically little knowledge or interest in the analysis embodied in the template; they are responsible for executing existing decision templates that result in variant designs that require only parametric changes in the original decision templates. Ming and co-authors [15] present the ontologies developed for selection decision, compromise decision, and hierarchical coupled decisions using the software tool Protégé [16]. The classes and properties of the relevant ontologies are defined by Ming and co-authors (see [17, 18]). Ming and co-authors [14] present the very first version of platform PDSIDES which is web-based and deployed in the local server of the Systems Realization Laboratory at the University of Oklahoma.

PDSIDES has the potential to support a human designer with the identified core competencies for product realization when integrated with the cloud. In Fig. 1, we illustrate the concepts underlying the foundations and principles of Cloud-Based Platform for Decision Support in the Design of Engineering Systems (CB-PDSIDES) as proposed in this paper. To integrate PDSIDES with cloud and bring-in the concepts of cloud computing and collaboration into product design and manufacturing, we adopt the definition for cloud-based design and manufacturing as proposed by Wu and co-authors [7]: "Cloud-Based Design and Manufacturing refers to a product realization model that enables collective open innovation and rapid product development with minimum costs through a social networking and negotiation platform between service providers and consumers. It is a type of parallel and distributed system consisting of a collection of inter-connected physical and virtualized service pools of design and manufacturing resources (e.g.: parts, assemblies, CAD/CAM tools) as well as intelligent search capabilities for design and manufacturing solutions."

In this paper, we present PDSIDES Version 2.0, namely, Cloud-Based PDSIDES (CB-PDSIDES). CB-PDSIDES is currently developed to run in a virtual machine on Google Cloud Computing Engine. The platform PDSIDES integrated with the cloud has in its core a decision support gene. We address two types of decision support genes via CB-PDSIDES: compromise and selection decision support problems (known as cDSP and sDSP, respectively) [19, 20]. The execution of decision support genes on a computer is foundational to the platform to realize complex engineered systems. The developed ontologies for selection decision, compromise decision, and hierarchical coupled decisions are implemented in CB-PDSIDES for representing decision workflows. In Fig. 1, we illustrate the concept of CB-PDSIDES with the cDSP construct at its core as the fundamental decision support construct. The problem-specific information (declarative knowledge) is captured using the cDSP via the keywords *Given*, *Find*, *Satisfy*, and *Minimize*. Procedural knowledge is associated with how the information transformation is carried out and details how the transformation is executed via a decision workflow or decision network. This is captured via

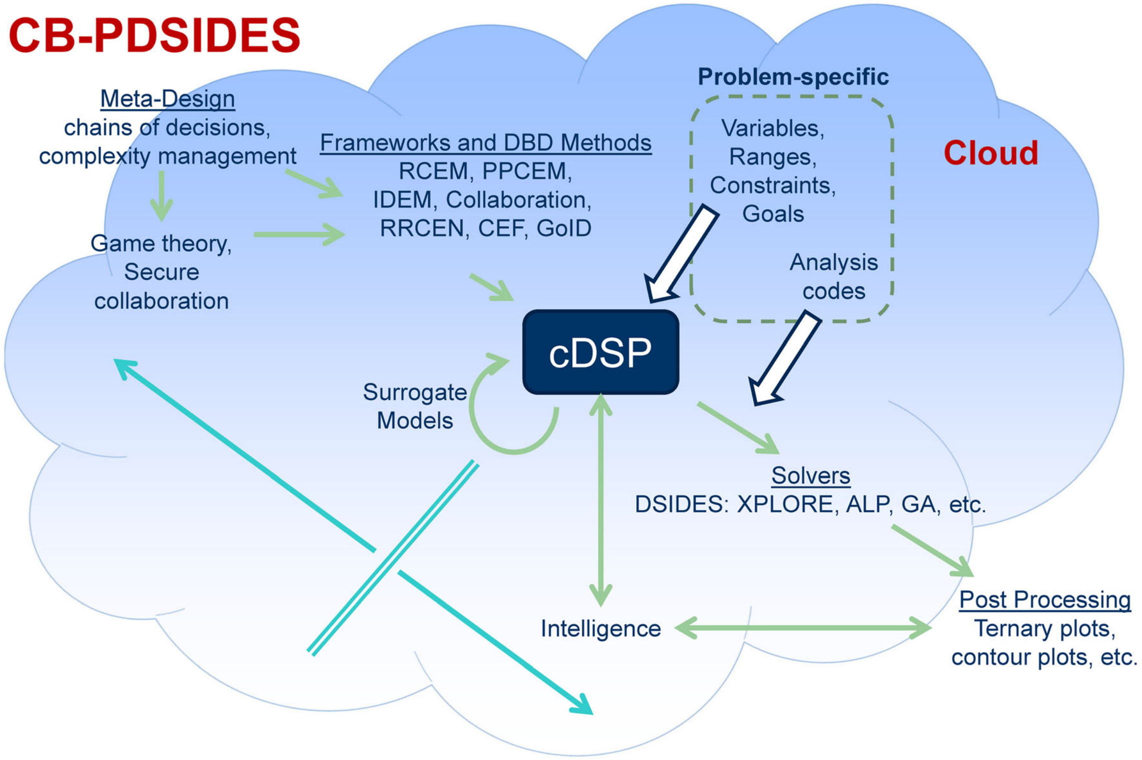


Fig. 1 An illustration of the Cloud-Based Platform for Decision Support in the Design of Engineering Systems concept

decision-based design templates like *process template*, *sDSP template*, *cDSP template*, *surrogate modeling template*, *design space exploration template*, and *robust design template* [21]. The analysis codes and simulations associated with the problem framed are also communicated to the decision support construct, see Fig. 1. Surrogate modeling techniques and tools are available in the platform via the *surrogate modeling template* to support the designer in managing the complexity and coming up with reduced order models (see [21] for details). Post-processing tools like ternary plots and contour plots that are automated with rules are available via the *design space exploration template* to help the designer easily explore the solution space and identify robust solution regions of interest by managing uncertainty (see [21] for details). Frameworks and design methods anchored in the decision-based design paradigm that incorporates the decision support genes (cDSP or sDSP) are incorporated in the cloud-based platform to support the designer to formulate and execute design problems systematically. These include Robust Concept Exploration Method (RCEM) [22], Product Platform Concept Exploration Method (PPCEM) [23], Inductive Design Exploration Method (IDEM) [24], Concept Exploration Framework (CEF) [25], Goal-oriented Inverse Design (GoID) Method [26], and GoID Method with robustness [9, 27]. Integrated knowledge, i.e., integration of declarative and procedural knowledge, is captured via the design methods and frameworks available in the platform. The computational solvers associated with the execution of problem formulated like DSIDES (Decision Support in the Design of Engineering Systems) [28] for cDSP construct are available to be accessed via the cloud. Collaborating designers can access the cloud-based platform from different parts of the world to share information and formulate design problems worthy of further exploration. The knowledge associated is captured and stored in CB-PDSIDES and can be retrieved and shared instantly via cloud with the collaborators depending on the design requirements. The issues of collaboration and information sharing are also addressed as collaboration and communication is key in the Cloud-Based PDSIDES. This is addressed via paradigms like crowd-sourcing, mass collaboration, and social product development [3].

Architecture of Cloud-Based PDSIDES

In Fig. 2, we show the architecture of CB-PDSIDES. The computing architecture for CB-PDSIDES follows the architecture of cloud-based design and manufacturing systems proposed by Wu and co-authors [29]. The architecture of CB-PDSIDES includes five layers: (i) user layer, (ii) web portal layer, (iii) logic layer, (iv) virtual layer, and (v) physical layer.

Since CB-PDSIDES is deployed in the cloud, users can gain access to CB-PDSIDES via PCs and smart phones over the internet. The web portal layer of CB-PDSIDES includes the user interaction GUI for accessing the design templates available. The user interaction GUI includes the following: template searching and browsing GUI which are designed

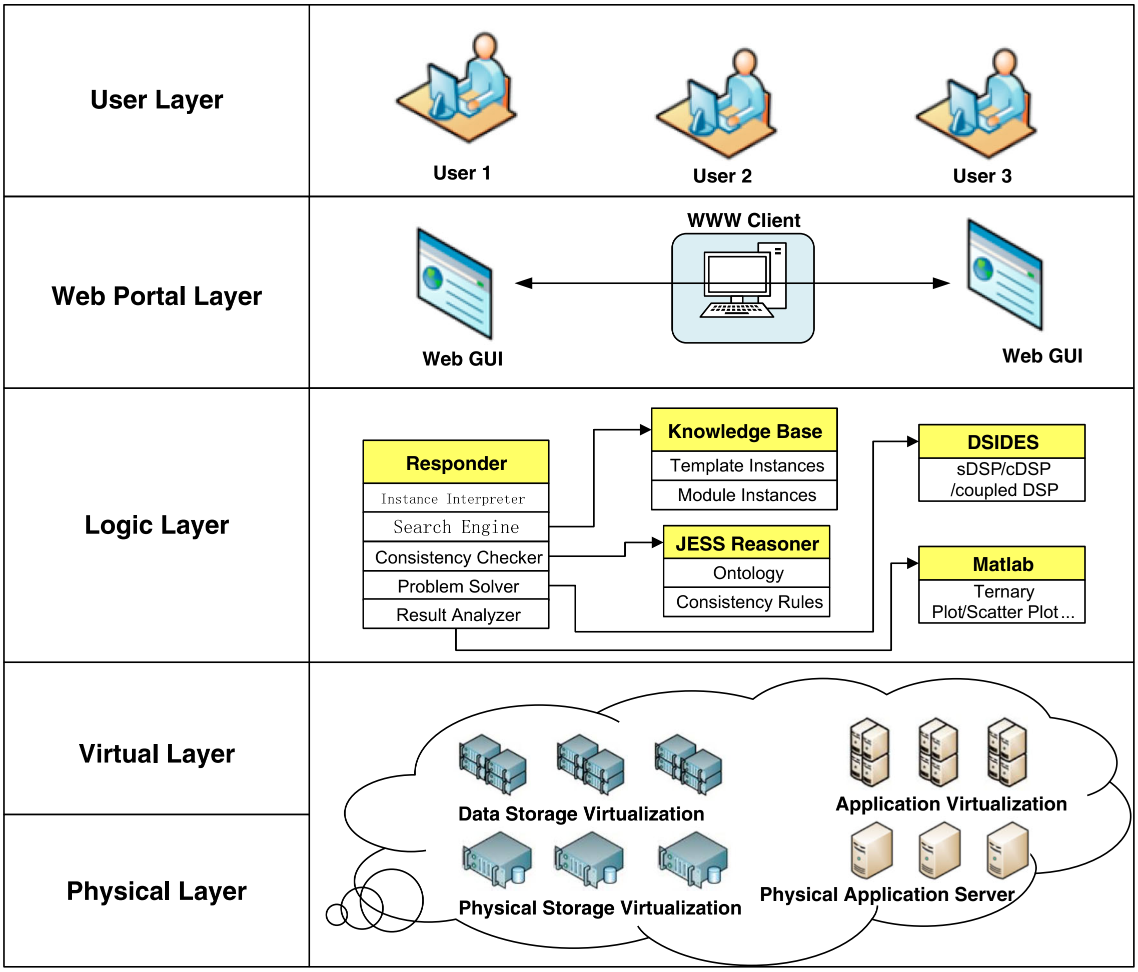


Fig. 2 Computing architecture of CB-PDSIDES

for locating the required DSP templates and presenting them; template creating and editing GUI which are designed based on the DSP template structures for the purpose of instantiation and modification of the DSP templates; and the template execution and analysis GUI which are designed for executing DSP templates and performing post-solution analysis. The GUI is allowed to communicate with the logic layer of CB-PDSIDES by a request-response mode using the Hyper Text Transfer Protocol (HTTP). The logic layer of CB-PDSIDES includes five main parts, namely, Response Server, Knowledge Base, JESS Reasoner, DSIDES, and MATLAB. The Response Server is the central "brain" that integrates the other four parts for responding to requests. The Response Sever itself has five components including a search engine, an instance interpreter, a consistency checker, and a problem solver. The instance interpreter is for interpreting the data collected from the template creators (or editors) and formatting it into DSP template instances according to the DSP ontologies. The generated template instances and module instances are stored in the Knowledge Base. The search engine is connected to the Knowledge Base to provide ontological semantic-based knowledge retrieval. Consistency checking is facilitated through a consistency checker together with the JESS Reasoner—the Rule Engine for the JavaTM Platform, which provides rule-based intelligence inference. The problem solver is connected to DSIDES for solving the DSPs. DSIDES (Decision Support in the Design of Engineering Systems) is a tailored computational environment that supports the execution of the decision support problem templates. DSIDES is invoked when a template executer executes a DSP template. The result analyzer is included to help users especially template implementers analyze the results produced by the problem solver, DSIDES. MATLAB and its features support data visualization tools such as ternary plots and scatter plots for visualizing the DSP results and further carry out solution space exploration. Therefore, MATLAB and its features for visualization and solution space exploration are integrated to CB-PDSIDES to support post-processing. The virtual layer and physical layer in CB-PDSIDES support data storage and retrieval for multiple users who are connected via cloud thereby establishing a networked collaborative environment. As noted by Wu and co-authors [29], through virtualization, the computing resources of CB-PDSIDES like the DSP templates, solvers, post-processing resources, and data storage are separated from physical computing hardware and reallocated dynamically to the different applications based on the needs of users. Through this unified computing architecture of CB-PDSIDES, we are able to support multiple tenants through a single instance of the platform PDSIDES, defined as multitenancy [29]. These features of the computing architecture of Cloud-Based PDSIDES differentiates it from the other web-based services. In the next section, we present some of the core functionalities offered by CB-PDSIDES in ICME context for integrated materials and products realization.

Core Functionalities Offered by CB-PDSIDES in ICME Context

CF1: Modular Reuse of Design Workflows Along a Design Process (Knowledge Management)

Core functionality 1 (CF1) is the capability of CB-PDSIDES to support a designer in designing new design workflows by reusing past knowledge from similar design problems. Specifically,

1. Support for reusing and reconfiguring workflows for different conditions and problems;
2. Reconfiguring the computational workflow developed for one product to the design of another product.

CF1 is possible using CB-PDSIDES by means of an ontology that provides a common vocabulary for representing domain-specific knowledge. The ontologies for representing the knowledge captured via the decision support genes, cDSP and sDSP, have been developed and form the foundations for CB-PDSIDES (see [] for details). A PEI-X (Phase-Event-Information-X) ontology for meta-design is included in CB-PDSIDES for designing decision workflows. Details regarding the ontologies developed are available in [14, 18, 21].

The focus from the ICME context is on concurrently exploring the design space of both the products and the materials and narrow the set of possible options in the shortest possible time with minimum expense. Hence, instead of exploring the complete design space from first principles using detailed models, the focus is on exploring simplified models that are good enough to compare different design alternatives. Additionally, the notion of designing the workflows by reusing past knowledge from similar design problems is important because of the following:

1. Evolving simulation models, resulting in multiple fidelities of models at different stages of a design process, and
2. Significant model development and execution costs, necessitating judicious use of resources.

Moreover, the needs for accurate information depend on whether the goal is to narrow down the alternatives to a specific class of materials (i.e., during early design phase) and products or to design the composition and structure of a specific material system (i.e., during the later stages of design). To support the need to generate information at variable fidelities during the design process, the following features are offered via CF1 by CB-PDSIDES:

1. Support for reusing and reconfiguring workflows for different conditions and problems;
2. Support for complexity and uncertainty management: provide computational techniques to measure how complexity and uncertainty changes by replacing different components of the workflow;
3. Model management and knowledge-based idealizations: representation of models at different levels of abstraction, along with information about their accuracy.

CF2: Design Workflows in Distributed Collaborative Settings

CF2 is the capability of CB-PDSIDES to support designers in design collaborations. CF2 is possible using CB-PDSIDES through a Secure Co-Design (SCD) Framework that uses information theory [30, 31] and game theory [32, 33] protocols to identify co-design solutions while preserving confidentiality of the information shared between the participating design collaborators.

From the ICME context, this could be a scenario where components are designed by one organization and materials are designed by another organization where information and knowledge sharing needs to be managed. An example of this could be a product-level cDSP formulated by product designers and a material-level cDSP formulated by materials scientists. Let us assume that the material scientists have proprietary models that they do not wish to share (explicitly or implicitly) with the product designers. In a similar sense, the product designers do not wish to share all the information in the product-level cDSP with material scientists. However, both parties would like to jointly design the product and the material and are connected to each other via cloud. The collaborative nature of the design process induces additional design issues from ICME context to be addressed for the management of design workflows, such as the following:

1. Collaborative authoring of workflow templates (check for consistency among collaborating entities)

2. Privacy-preserving collaboration in integrated products and materials design.

CF3: Reduced Cost of Computation and Management of Complexity

There are several methods for simulating various aspects of materials' manufacture and product design. However, it can be very costly and time-consuming to compute and re-compute these simulations in the process of design, especially in the early stages of design where it is desirable to explore a wide range of options rather than developing detailed designs. For situations like this, there are several ways of developing surrogate models (metamodels) which rapidly provide design information; each of these will give metamodels of different degrees of accuracy at different costs which may be used at different stages of design (see [34, 35] for details). There is thus a need to assess the benefits of using different metamodels in different stages of design and compare these with the costs of developing these metamodels. Using metamodels of increasing fidelity in a design process is one way of exploring the design space; an alternative way is by using robust design with decreasing bands of robustness. The advantages and limitations of each of these approaches has to be considered. To support the need to reduce computational cost and manage complexity, CB-PDSIDES offers the following capabilities:

1. Support to develop reduced order models of various degrees of fidelity using simulations and assess reductions in computational costs when using these models.
2. Support to combine the use of metamodels with varying degrees of robust design and assess tradeoffs between accuracy and computational costs.

This functionality is addressed by two modules in *design space exploration* (DSE) *process template* ontology in CB-PDSIDES (see [21] for details). The DSE process template has three sub-templates: *problem model* (PM), *compromise decision support problem* (cDSP), and *post solution analysis* (PSA). The *problem model* (PM) sub-template in DSE process template has two modules: *theoretical and empirical model* and *surrogate model*. The *theoretical and empirical model* module is used to capture the information and knowledge associated with already existing and available material and product models. An example for this is capturing the information and knowledge associated with an existing constitutive material model in literature that establishes stress as a function of strain, strain rate, temperature, and other material internal variables. The *surrogate model* module is used when there is a need to develop reduced order models or meta-models that captures the relationships between responses and the corresponding factors. Template instances of the surrogate models developed are stored as new knowledge in CB-PDSIDES to facilitate reuse. Collaborating designers are able to use the cloud to develop, share, and use models to formulate design problems using CB-PDSIDES.

CF4: Cost-Efficient Integration of Templates for Product Development—Carry Out Meta-Design

CF4 is the capability of a designer to use CB-PDSIDES in exploring the effects of changing the ways in which templates are integrated on the outcomes of the design workflows. This is achieved in a modular fashion by means of a 3-P information model proposed by Panchal and co-authors [30]. The three P's refer to the key design information elements—*product*, *problem*, and *process*. Each of these is defined in an independent modular fashion. Designing a product is possible by using different types of un-instantiated problem and process templates. Examples of different possibilities in problem template includes Archimedean cDSP formulation [36], preemptive cDSP formulation [19], Robust Design Type I formulation [37], Robust Design Type II formulation [37], Type I, II, and III Robust Design formulation [38], Robust Design Type IV formulation [24], and traditional optimization. Examples of different possibilities in process template includes point-based iterative search, sequential design, set-based design, RCEM or CEF using response surface models [22], and goal-oriented inverse design of process chains [26]. Examples of the different product templates include design of pressure vessel [15], design of hot rod after rolling [39], design of slab after casting [40], and design of multiscale materials and products [41]. The benefit associated with this functionality from ICME context is the capability to realize configurations of different problems with different processes and applying these for a variety of product design scenarios. This leads faster product realization schemes in a cost-efficient manner as needed for ICME. Using the cloud, participating material scientists and designers are able to collaborate in the integration of templates for product development depending on their expertise—in problem, product, and/or process information elements.

CF5: Systematic Solution Space Exploration by Managing Uncertainty

Design and solution space exploration by considering system uncertainty is essential for the model-based realization of complex material/product systems via ICME. As discussed in "Frame of Reference," the models that are available are typically incomplete, inaccurate, and not of equal fidelity. Hence, seeking single point optimum solutions is typically not valid as these optimum solutions no more hold if any variations occurs—which is bound to happen with a complex material/product system. This necessitates the need for systematic design and solution space exploration to identify satisficing solutions that perform well and are relatively insensitive to the uncertainty present in the system—defined as robust solutions. Using the platform CB-PDSIDES, designers can collaborate from different parts of the world in formulating robust design problems and exploring the design and solution space using rules defined in the platform to identify solutions that are relatively insensitive to these variations. The exploration of the solution space provides designers with knowledge to refine or improve the model especially at early stages of design. This functionality is supported by the *post solution analysis* (PSA) sub-template within the *design space exploration* (DSE) template of CB-PDSIDES (see [21] for details). The three modules *Weight Sensitivity Analysis*, *Constraint Sensitivity Analysis*, and *Additional Requirements Analysis* that form part of PSA sub-template of CB-PDSIDES are used depending on the requirements of the problem to explore and visualize the solution space and identify solutions that are relatively insensitive to uncertainty. The designers are able to formulate a robust design problem by instantiating a Type I, II, III, or IV Robust Design Problem template in CB-PDSIDES.

CF6: Cloud-Based Design Communication—Instant Feedback Across Design Workflows

A key goal in design is the proper communication of design process. Wu and co-authors [7] identify the key issue of fully understanding a complex design process in order to improve design communication. The key issue includes design tasks that need to be completed, the source for specific information that is needed for design, the individual to be contacted for the right information, the extent of distortion in the information available, and the extent to which the distorted information affects design. As discussed in "Frame of Reference," traditional product design paradigms are limited as design communication is a one-way mapping in a linear sequence across design phases/domains. PDSIDES in the cloud settings will improve design communication through multiple information channels facilitated by cloud. This will allow for information flow in multiple directions facilitating dynamic changes during product development and instant communication between the different design domains. Assume that each stage of product realization starting from function to final manufacturable product descriptions involves distributed designers. PDSIDES facilitates a decision network where information is shared in a one-way fashion. CB-PDSIDES however can facilitate collaboration and can result in a two-way and multi-way network for product realization where the distributed designers are connected through the cloud. In the next section, we demonstrate the core functionalities discussed via an industry-inspired problem.

Cloud-Based Design of Materials and Products—Design of a Hot Rolled Steel Rod Example

The core functionalities CF1 (modular reuse), CF3 (manage complexity), CF4 (meta design), and CF5 (solution space exploration) are essential to the platform PDSIDES and have been tested using several example problems (see [14, 15, 18,]). In this paper, we focus on demonstrating the core functionalities CF2 (design workflows in distributed collaborative settings) and CF6 (instant feedback across decision workflows) that are prominent to CB-PDSIDES—design workflows in distributed collaborative settings and cloud-based design communication. We define collaboration in this context as the sharing of information, knowledge, and resources between designers either in a sequential (leader-follower) or a concurrent (co-operative) manner. In order to demonstrate the functionality CF2, we view collaboration as the sequential fashion of information sharing where the first designer shares the design decisions with the second, following which the second designer makes their respective design decisions. Later, we discuss the concurrent fashion of collaboration where complete information is shared instantly with all the designers. We demonstrate these two core functionalities of CB-PDSIDES by means of an industry-inspired example problem, namely, the design of a hot rolled steel rod (see [25, 26] for details regarding the problem).

Problem Description Steel manufacturers are focused on developing newer grades of steel with improved mechanical properties and performances at the product level. A steel rod is a product produced after several manufacturing processes like casting, reheating, and hot rolling and further used to develop automotive components like gears. In order to produce a gear with specified properties, there is a need to design the rod (semi-product) to satisfy certain defined mechanical properties. These mechanical properties however are defined by the microstructure, chemical composition, and processing of the steel. Hence, there is a need to design the microstructure and processing route of the steel to achieve the target mechanical properties desired for the rod. The mechanical properties that we focus on for the rod are yield strength, tensile strength, and hardness. These mechanical properties depend on the material microstructure like ferrite grain size and phase fractions of ferrite and pearlite which in turn are defined by the initial austenite grain size, carbon and manganese concentrations, and cooling rate during the cooling process after rolling. The problem-specific requirements and goals are detailed by Nellippallil and co-authors [26] and are not repeated here. In this problem, there are three decision makers—*customer*, *product designer*, and *materials designer*. Customer specifies the requirements from the market side—this could be changing performances for the product depending on the type of applications as specified by industrial experts. Product designers are focused on designing the end product—in this case, the hot rolled and cooled rod. Materials designers are focused on designing the microstructure factors in order to realize the product.

Goal-oriented Inverse Design Method In goal-oriented inverse design method [26], the designer starts with the end performance requirements for the product and designs the whole system in an inverse manner to meet these end performance goals. In Fig. 3, we represent the four design domains of product development on the axis of the quadrant as CA (customer attributes), FR (functional requirements), DP (design parameters), and PV (processing variables). In the lower right quadrant is the *production domain* involving *process variables* and their relationship to design parameters (numbered 3 in Fig. 3). In the upper right quadrant is the *engineering domain* involving *design parameters* and *functional requirements* (numbered 2 in Fig. 3). In the upper left quadrant is the *customer domain* involving *functional requirements* and their dependencies to *customer requirements* (numbered 1 in Fig. 3).

In this paper, we adopt a customer-centric perspective towards product realization where the customer attributes/needs (CAs) are the performance desired for the product. The product-level properties are the functional requirements (FRs); the microstructure of material is the design parameters (DPs) in physical domain that define the product properties. The processing variables are the process variables (PVs) in process domain that define the microstructure. The mapping of the design domains in terms of the processing-structure-property-performance is shown in the lower left quadrant in Fig. 3. Using goal-oriented inverse design (GoID) method, we start from the product performance (numbered 1 in Fig. 3) and design first the product properties to meet the performance (numbered 2 in Fig. 3) and further, the material microstructure to meet the properties (numbered 3 in Fig. 3) in an inverse manner (see Fig. 3).

In CB-PDSIDES, using the decision workflow design panel, a decision workflow for the hot rolling problem is created, as shown in Fig. 4. Two decisions are defined in terms of cDSPs—a product design cDSP (created by *product designer*) and a materials design cDSP (created by *materials designer*). Detailed description of the cDSP template instantiated for the product using CB-PDSIDES is shown in Fig. 5. Using the template in Fig. 5, the product designer captures the information associated with designing the rod like the problem variables, parameters, constraints, goals, and preferences. More details on the execution of this template is available in [14]. The execution in this decision workflow is sequential where

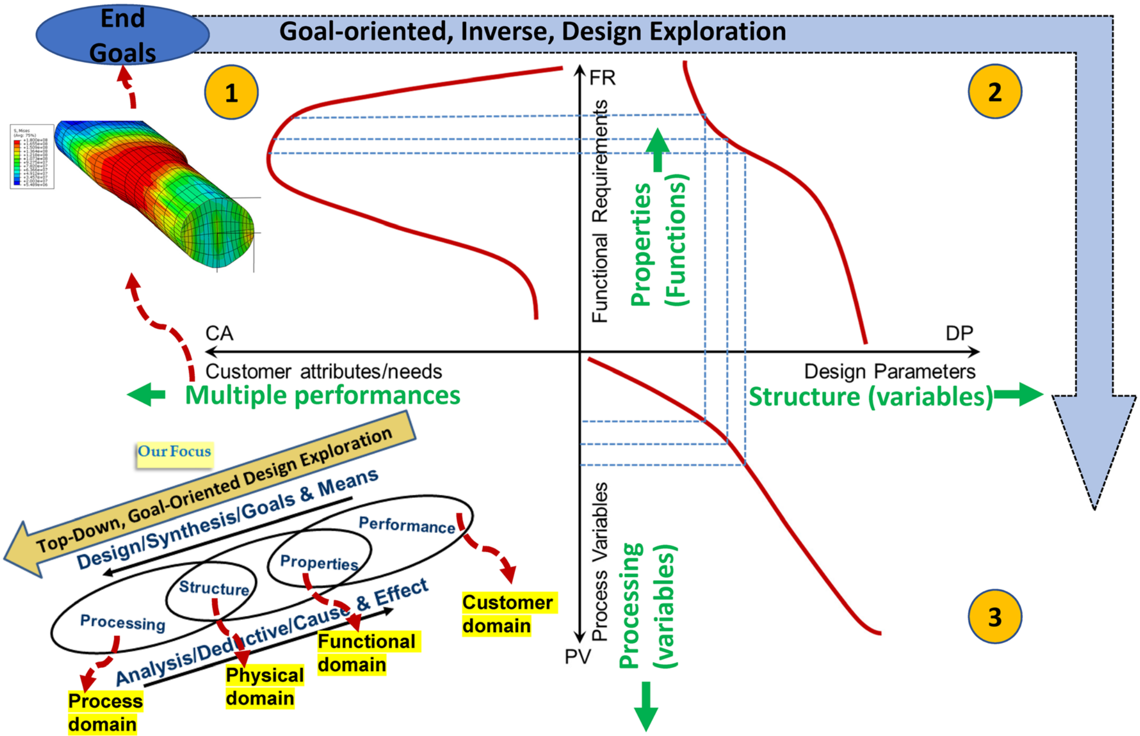
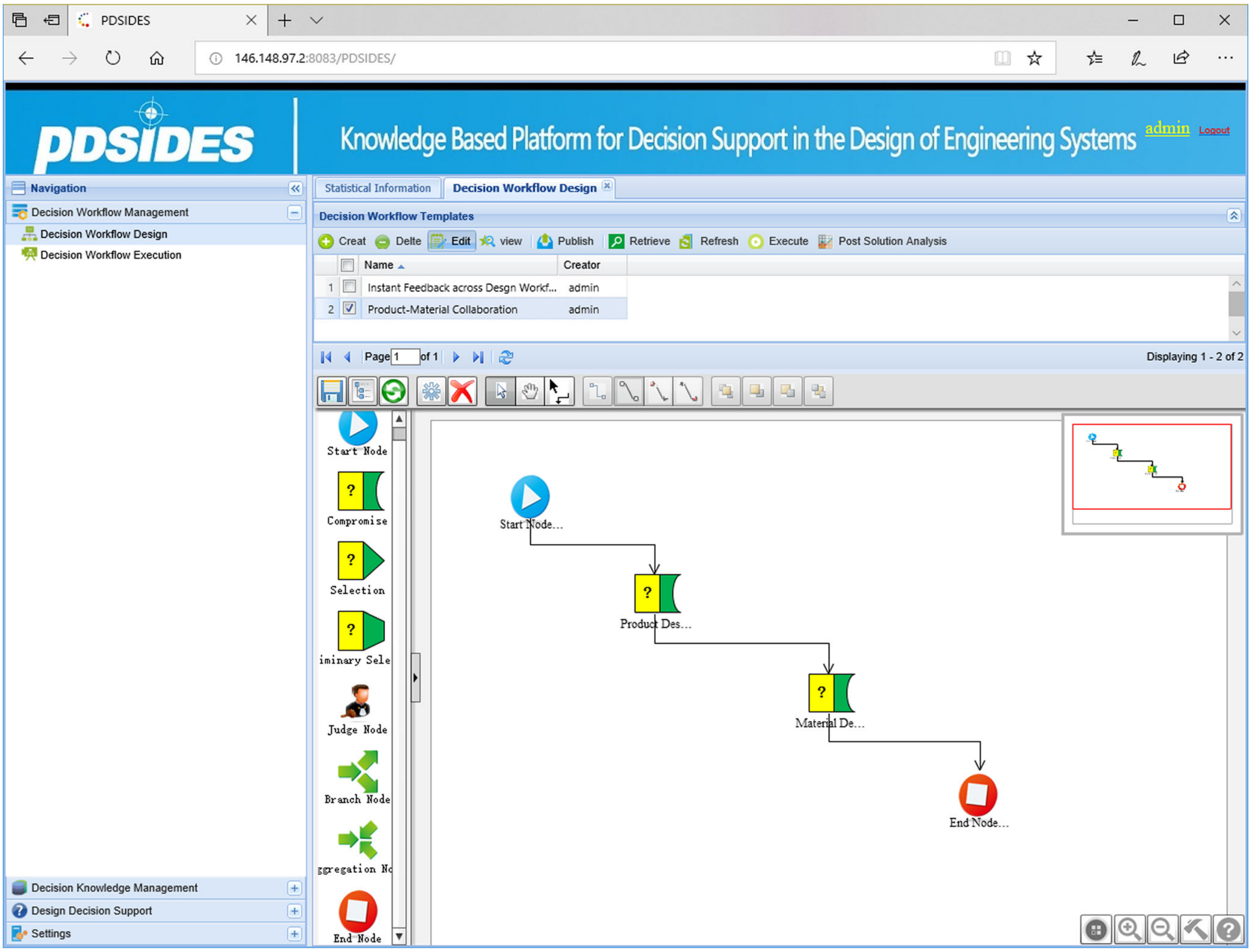


Fig. 3 The customer-centric product realization process



		Name	Creator
1	☐	Instant Feedback across Desgn Workf...	admin
2	☑	Product-Material Collaboration	admin

Page 1 of 1

Displaying 1 - 2 of 2

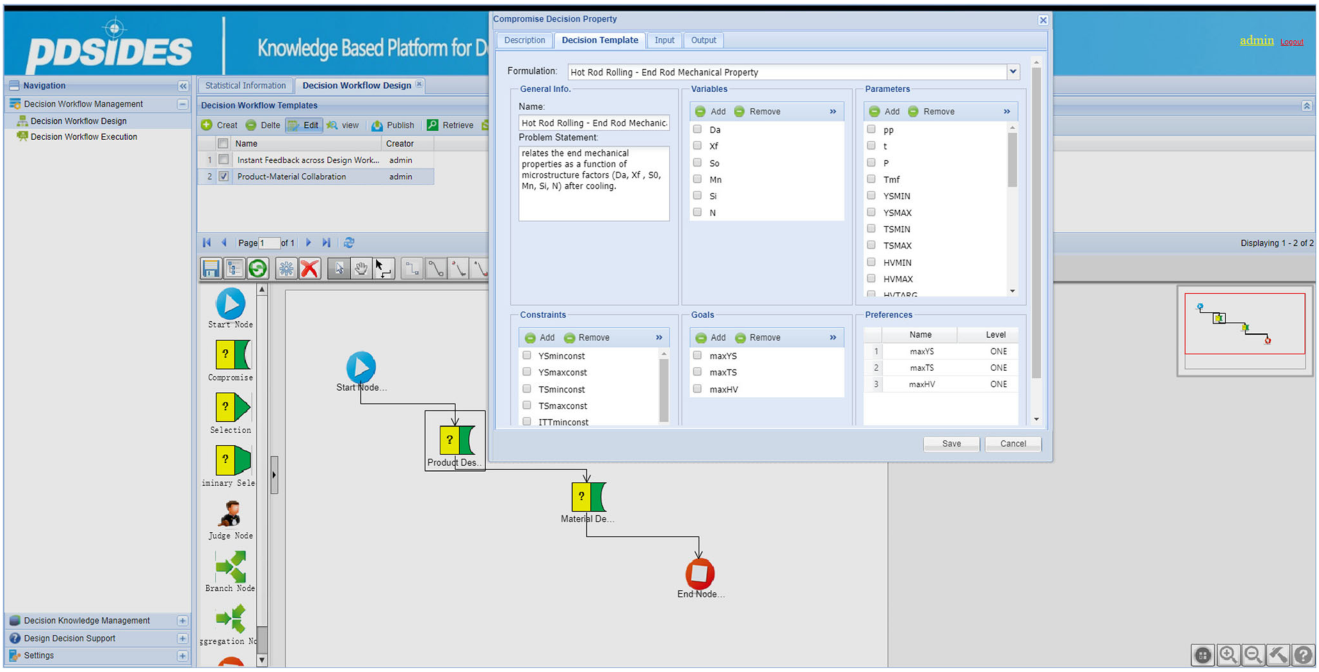
Fig. 4 Decision workflow in CB-PDSIDES illustrating collaboration between product design group and material design group

the product designer first executes the product design DSP and communicates the results via cloud to the collaborating materials designer (see [26] for details). After analyzing the results obtained, the material designer further executes the material design cDSP to further make decisions. The results for this sequential execution of cDSP templates following the GoID method to design the hot rolled is described by Nellippallil and co-authors [26] and are not repeated here.

The major advantage of using cloud-based design is the core functionality CF6 (instant feedback across decision workflows)—where the designers are able to instantly communicate and provide feedback between decision workflows. From the problem perspective, this is needed when there are sudden changes in customer demands so that the product designer and material designer are required to change their design instantly to meet the new customer requirements. Thus, there needs to be dynamic changes in design depending on the market requirements.

PDSIDES in its original form has the potential to facilitate one-way communication via decision workflows. Integrating PDSIDES in the cloud settings will improve design communication through multiple information channels as facilitated by cloud. This will allow for information flow in multiple directions thereby facilitating dynamic changes during product development and instant communication between the different design domains like customer and physical domains or functional and process domains, as shown in Fig. 6. CB-PDSIDES thus can facilitate collaboration (in concurrent fashion) and can result in a two-way and multi-way network for product realization where the distributed designers are connected through the cloud. This facilitates dynamic product updates, design changes, and feedback in the product realization process.

In Fig. 7, we show the decision workflow for the hot rolling problem with the three stakeholders—customer, product designer, and materials designer. In this configuration, all the stakeholders are connected via cloud. The black lines denote the forward connection between the stakeholders. The red lines denote the instant feedback communication between the stakeholders. Thus, as can be seen in



	☐	Name	Creator
1	☐	Instant Feedback across Design Work...	admin
2	☑	Product-Material Collabration	admin

Formulation: Hot Rod Rolling - End Rod Mechanical Property

General Info.

Name: Hot Rod Rolling - End Rod Mechanic

Problem Statement: relates the end mechanical properties as a function of microstructure factors (Da, Xf , S0, Mn, Si, N) after cooling.

Variables

- ☐ Da
- ☐ Xf
- ☐ So
- ☐ Mn
- ☐ Si
- ☐ N

Parameters

- ☐ pp
- ☐ t
- ☐ P
- ☐ Tmf
- ☐ YSMIN
- ☐ YSMAX
- ☐ TSMIN
- ☐ TSMAX
- ☐ HVMIN
- ☐ HVMAX
- ☐ HVTARG

Constraints

- ☐ YSminconst
- ☐ YSmaxconst
- ☐ TSminconst
- ☐ TSmaxconst
- ☐ ITTminconst

Goals

- ☐ maxYS
- ☐ maxTS
- ☐ maxHV

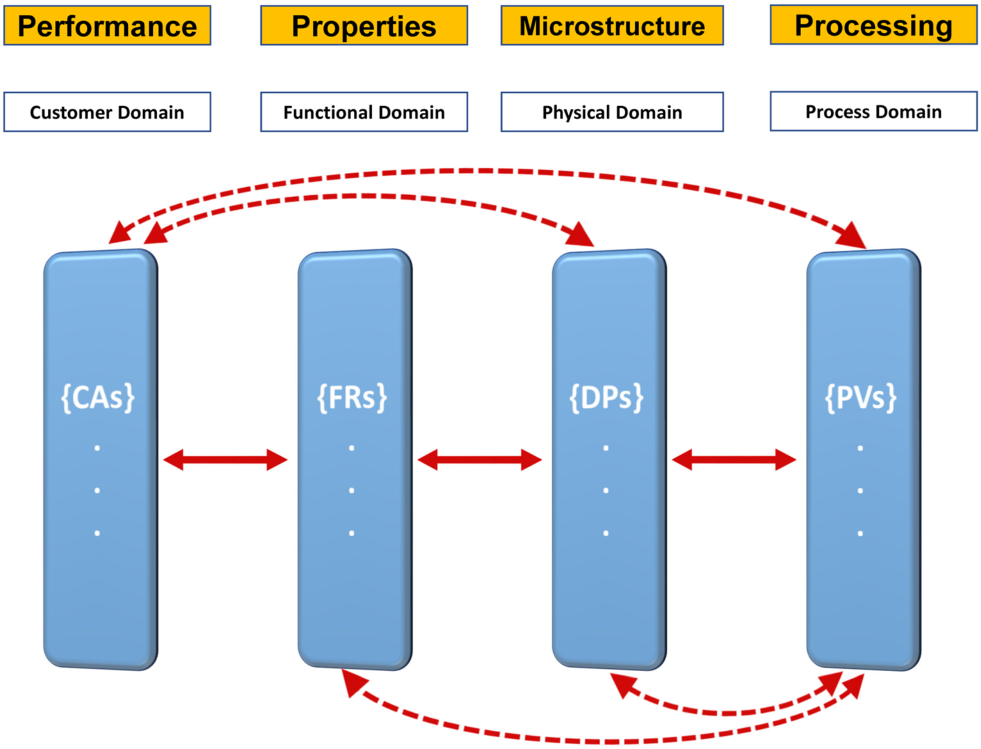
Preferences

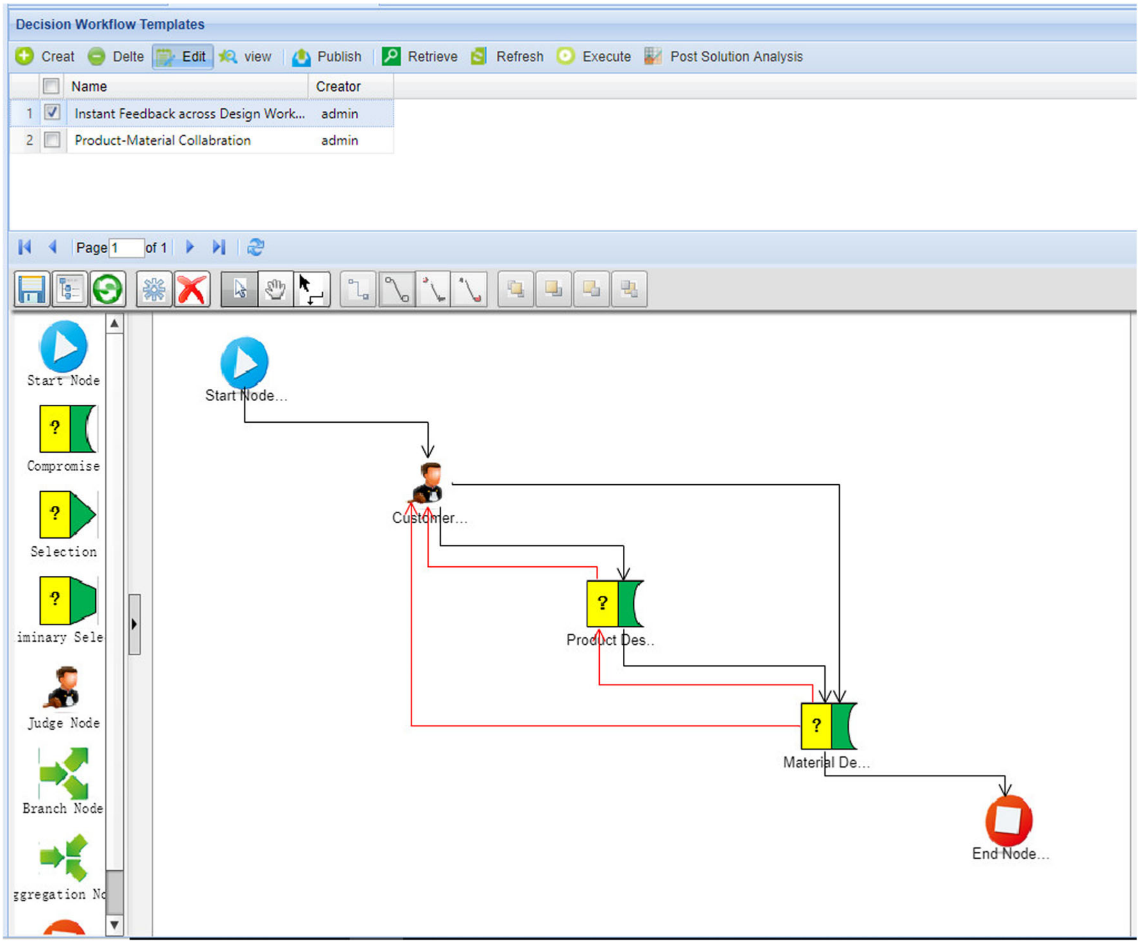
	Name	Level
1	maxYS	ONE
2	maxTS	ONE
3	maxHV	ONE

Fig. 5 Detailed description of cDSP template instantiated by product designer

Fig. 7, there is a direct two-way mapping between customer and product designer; customer and material designer; and product designer and materials designer, facilitated via the cloud. This is a networked decision workflow in the cloud that facilitates instant communication and feedback between decision points. Such a networked configuration promotes a true collaborative environment for design and supports the integrated design of materials, products, and associated manufacturing processes. In this configuration, designers are able to share information, knowledge, and design/manufacturing resources instantly so as to facilitate co-creation of value in a more cost-effective manner.

Fig. 6 Illustration of communication via information channels using cloud-based design for materials and product realization




Decision Workflow Templates

	☐	Name	Creator
1	☑	Instant Feedback across Design Work...	admin
2	☐	Product-Material Collabration	admin

Fig. 7 Networked decision workflow in CB-PDSIDES

Dynamic changes are easily incorporated, and the design decisions are communicated across the network making the whole product realization process faster and efficient.

CB-PDSIDES and Broader Applications

In this section, we discuss the broader applications of CB-PDSIDES and how CB-PDSIDES integrates with and complement different other projects and products. CB-PDSIDES is developed as a tool for cloud-based design decision support that supports multiple applications and problem requirements. Complex system design problems that can be represented by modeling a workflow of compromise and selection decisions from a decision-based design perspective are addressed using CB-PDSIDES. In Fig. 8, we show some of the applications and examples of focus for CB-PDSIDES. We explore the applications of CB-PDSIDES for the following

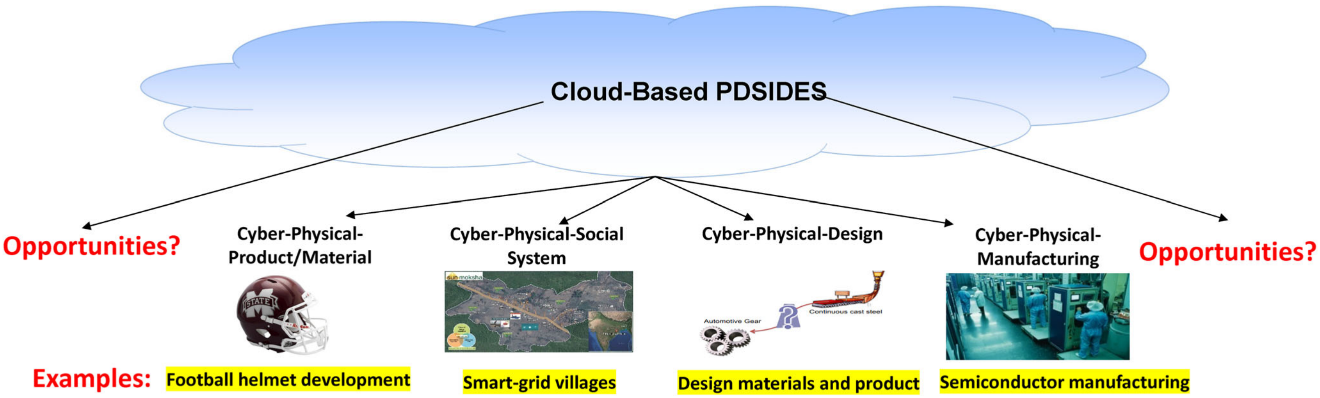


Fig. 8 Broader applications of CB-PDSIDES

Cyber-Physical-'X' systems. The 'X' here denotes product/material, social, design, or manufacturing systems, respectively, depending on the application of focus. We discuss each of these applications briefly in this section.

Applications to Cyber-Physical-Product/Material Systems

From the ICME context, we are interested in designing the next generation of cyber-physical-product/material systems. Design of products, sub-components, and materials with improved system-level performance goals is the major focus here. One application area of focus is the design of American football helmets. The goal-oriented inverse design method and Concept Exploration Framework (CEF) incorporated into the CB-PDSIDES platform are used to design two components (composite shell and foam liner) of an American football helmet by Fonville and co-authors [42]. The performance goals defined for the helmet in this problem include dissipation of impact energy, mitigation of stress waves, and minimization of helmet weight (see [42]). The larger vision here is to design products, sub-components, and materials using multi-scale modeling efforts and system-based robust design techniques so as to achieve the integrated design exploration of multiscale, multifunctional materials and products.

Applications to Cyber-Physical-Design

One other application of focus for CB-PDSIDES from the ICME domain is in cyber-physical design. An application example is the design of steel manufacturing process chain discussed in this paper. PREMΛP—Platform for Realization of Engineered Materials and Products—is developed by TCS Research, Pune, as a comprehensive IT platform that facilitates the integration of models, knowledge, and data for designing both the material and the product [43]. The platform PREMΛP is developed for different types of users like expert users, non-expert end-user, and for researchers. Gautham and co-authors [43] define the domain-independent and domain-dependent components of PREMΛP. The CB-PDSIDES presented in this paper has the potential to support PREMΛP with several of its components. Based on the key functionalities proposed for CB-PDSIDES, it is envisioned that CB-PDSIDES can support PREMΛP in *robust design and MDO*, *decision support*, *knowledge engineering*, *guided experimentation*, *product design*, and *product performance*.

Applications to Cyber-Physical-Manufacturing Systems

Application of CB-PDSIDES to cyber-physical-manufacturing systems is explored from the context of Industry 4.0. Smart manufacturing systems design in the era of Industry 4.0 demand a need to address the distributed and networked nature of manufacturing processes and their associated products. There is a need to design manufacturing systems that facilitate seamless data, information, and knowledge sharing between the different physical, cyber components of the system and the stakeholders (customers, suppliers, manufacturers, etc.) involved. Milisavljevic-Syed and co-authors [44] present a computational framework for design of dynamic management of such networked manufacturing systems from the context of Industry 4.0. It is envisioned to incorporate the framework and associated constructs to CB-PDSIDES with possible applications of design for dynamic management in steel manufacturing, additive manufacturing, health care systems, etc.

Applications to Cyber-Physical-Social Systems

CB-PDSIDES for automated micro-enterprise design and analysis for sustainable rural development of villages in India is also explored as an application to cyber-physical-social systems. Three constructs that support this application are (i) village-level baseline sustainability index, (ii) dilemma triangle, and (iii) village-level system dynamics, proposed by Yadav and co-authors [45]. Yadav and co-authors [45] present a computational framework incorporating these constructs to facilitate dialog between the stakeholders involved: corporate social responsibility (CSR) investors and social entrepreneurs. These stakeholders are geographically dispersed, and an increase in the number of stakeholders demands a need for them to effectively communicate and collaborate in order to come up with sustainable solutions (micro-enterprises) worthy of further investment. We envision incorporating the framework and constructs developed by Yadav and co-authors in CB-PDSIDES to facilitate collaboration and open innovation between these stakeholders. Using CB-PDSIDES, the stakeholders will be able to direct attention to issues and challenges that are typically ignored or missed while solving social wicked problems.

All these applications discussed are work in progress in the International Systems Realization Partnership between the Institute for Industrial Engineering at The Beijing Institute of Technology, The Systems Realization Laboratory at The University of Oklahoma, and the Design Engineering Laboratory at Purdue. Other collaborating institutions include Center for Advanced Vehicular Systems at Mississippi State University, Liberty University, SunMoksha, Tata Consultancy Research Pune, and the University of Liverpool.

Closing Remarks

To fully realize ICME and its capabilities in this digital era, there is a need to facilitate a network of participants, which includes material scientists, systems designers, software developers, and end service customers to come together and share material/product/manufacturing process/market data, information, knowledge, and resources instantly and collaborate so as to facilitate a cost-effective co-creation of value supporting open innovation. In this paper, we identify the requirements for a cloud-based computational platform (CB-PDSIDES) to support the integrated design of materials and products as required by ICME. The core competencies needed for a designer using the cloud-based platform for implementing an ICME-driven product realization in industry are identified. Based on these core competencies, we propose a cloud-based computational platform and the core functionalities offered by the platform in keeping with the ICME construct for cloud-based decision support. A hot rolling example problem for the production of a steel rod is used to demonstrate two core functionalities associated with CB-PDSIDES and some preliminary results are presented. The domain-independent cloud-based platform proposed supports designers in seamless, yet controllable, information, knowledge, and resource sharing. Further work and development are needed to successfully institutionalize ICME in industry using the technologies associated with Industry 4.0. Addressing the impacts of other technologies related to Industry 4.0 like big data, Internet of Things (IoT), and cyber-physical-product/material (CPP/M) systems on the goals defined for ICME needs to be carried out in the future to bridge these two transformational domains.

Acknowledgments Anand Balu Nellippallil thanks the Systems Realization Laboratory, University of Oklahoma, for supporting him.

Funding Information This work was financially supported by Tata Consultancy Services Research, Pune (Grant No. 105-373200) and by the John and Mary Moore Chairs and L.A. Comp Chair at the University of Oklahoma.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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