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Evaluating the effectiveness of InDeaTe tool in supporting design for sustainability

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Research Article

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Abstract

In today's aggressive global market, innovation is key for success and design solutions require not only to achieve competitive edge, but also to address the growing environmental, social, and economic needs of the community at large. Consideration of these three pillars of sustainability makes a design inclusive, and life cycle thinking is found to be a promising approach across the literature. However, most supports for design address certain facets or aid singular tasks, and the use of design methods and tools, which have the potential to significantly improve the design process, is low due to inappropriate use and selection of these methods. InDeaTe (Innovation Design database and Template) is a holistic, knowledge-driven, computer-based tool for design of sustainable systems, such as products, manufacturing systems andservice systems and has been developed to address and integrate the aspects of sustainability on a singular design platform. It comprises of the generic design process Template that imbibes life cycle thinking into the process by incorporating consideration of every life cycle phase in each design stage, where design activities are performed iteratively. It further supports the design process by aiding the use and selection of appropriate design methods and tools in concurrence with the primary motivation of improving sustainability of the system with the aid of the InDeaTe Design Database. This paper discusses the ontological underpinnings behind the conceptualization of the InDeaTe methodology and the development of the supporting tool. The paper further reports empirical findings from six different case studies conducted for evaluating the effectiveness of InDeaTe tool in supporting design for sustainability (DfS). The results show that InDeaTe tool has potential in supporting DfS.

Introduction

Sustainability is an important performance indicator of a system, be it – a product, manufacturing system, service system, integrated product-service system – and requires to be planned for during the design stages. A number of computer-based tools are available for sustainable design, such as a CAD-integrated DFE workbench tool (Roche *et al.*, 2001), use-phase analysis-matrix for environmental impact estimation (Oberender and Birkhofer, 2003), or the more commercially prevalent EcoIt, SimaPro, and Sustainable minds. However, these mainly support either a specific design activity, such as evaluation, or a specific life cycle stage, such as use-phase, and address one, such as environment, and not all three dimensions of sustainability. Therefore, there is an unaddressed area in supporting the design of sustainable systems in holistically addressing the various design activities, that is, generate-evaluate-modify-select (Srinivasan and Chakrabarti, 2010*a*) performed during the design process across each design stage (Pahl and Beitz, 1996), for the various life cycle stages of a system, with respect to all three dimensions of sustainability (Elkington, 1997). Furthermore, it has been reported that the implementation of methods and tools in the design process aids in performing an array of design tasks leading to the generation of a larger number of ideas (Lopez-Mesa, 2003) and an overall improvement in the design outcome (Chakrabarti and Lindemann, 2016). Büyüközkan *et al.* (2004) reported on a number of methods and tools for concurrent new product development and discussed internet-based collaboration as a promising platform towards inclusivity and agility. However, current design methods and tools, such as "Pinngate" (Sauer *et al.*, 2006), Competence support in Design and Development "CiDaD" (Ponn and Lindemann, 2006), the "Landscape of Methods" (Strasser and Grösel, 2004), the "Design Exchange" (Roschuni *et al.*, 2011, 2015), "IDEO Designkit" (Kelley *et al.*, 2013), "WikID" by Industrial Design Engineering at TU Delft (Vroom and Horváth, 2014), or "Amsterdam mediaLAB Design Method Toolkit" (Amsterdam, MediaLab., 2016), act mainly as repositories of methods and tools that are provided as an unconnected set of possibilities, without any systematic design process or methodology to bind them together across an overarching platform. Feng (2005) suggested a web-based collaboration between process planning and preliminary design activity and noted that a knowledge-base is a critical element of such a platform, while Costa *et al.* (2016) stressed on the need for

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an appropriate ontology-driven platform for knowledge-sharing that could be intelligent for approaching design. Thus, a support that can help orient the design intent toward sustainability and recommend pertinent knowledge, through a user-friendly computer interface, is currently missing. This is the key motivation for the development of the InDeaTe tool described in this paper.

InDeaTe (*In*novation *De*sign Database *a*nd *Te*mplate) is a knowledge-driven, computer-based, holistic support for design of sustainable systems, be these products, manufacturing systems, service systems, or a combination of these. It supports environmental, legislative, and competitive factors, during the design process, by (i) imbibing life cycle thinking into the design process through a generic design process template, (ii) incorporating sustainability definitions and their measures, collated from the literature, into the process for consideration, and (iii) aiding in the selection and use of appropriate design methods and tools from an expandable, ontologically tagged design database. This paper presents the theory and background behind the InDeaTe tool and reports the empirical findings from six case studies, conducted in two countries for two versions of the tool, to assess its effectiveness.

Literature review

Supporting life cycle thinking approach and sustainability

The "Brundtland Report" defined Sustainable Development (WCED, 1987: p. 43), including the dimensions of society and economy (Elkington, 1997) within the ambit of sustainability, thereby expanding well beyond "traditional environmentalism". To assess holistic progress, the need for "review of the whole system as well as its part" (Harris *et al*., 2001) and regard of the various implications "connected with every stage of a project's life cycle" (Vezzoli and Manzini, 2008) have been recommended. Thus, consideration of the entire life cycle of the system, termed as "Life Cycle Thinking", is an approach that is not only important for the assessment of issues in attaining sustainability, but also as a means for addressing these issues. It is the life cycle of the system, rather than the system in itself, that determines the overall sustainability of the system (Bras, 1997; Bhamra *et al*., 1999; Kota and Chakrabarti, 2014). The life cycle is determined during the design stages (Srinivasan and Chakrabarti, 2010*b*; Kota and Chakrabarti, 2014); therefore, in order to enable significant improvement in the sustainability of a system, a life cycle oriented, systematic approach is needed to be applied during the design process itself where most decisions are made on the system's life cycle (Ullman, 2003).

Over 80 sustainability "Definitions" are currently in use; each is open to interpretation, thereby requiring appropriation, with potential for use across a wide range of causes (Elliot, 1999). Sustainability "Principles" are less ambiguous and constitute the fundamental concepts that form the "basis for action" (Glavic and Lukman, 2007) toward "assessment activities" (Hardi and Zdan, 1997). Besides principles and definitions, policymakers also need "Methods" for assessing the effects of development so as to determine whether a development trend is sustainable or not (IAEA, 2005). "Indicators" offer that much needed appropriation by providing "comprehensive information about the systems shaping sustainable development" (IISD, 2012), thereby helping to "identify possible directions of changes" (Singh *et al*., 2009). Indicators help not only in measuring and calibrating progress toward sustainable development goals, but also in providing early warnings for prevention, sound decision-making, and effective action (UN-CSD, 2007). While sustainability Definitions imply the context and issues of *what* "sustainability" is, Principles provide frameworks or guidelines for *how* to address these issues; Indicators are *measures* that indicate the state of a system with respect to the pillars of sustainability. Together, these facets communicate the common vision of sustainability of a system and help clarify the design intent and develop requirements and solutions.

Supporting design methods and tools in practice

In the 1980s onwards, a number of significant contributions were made towards the development of Engineering Design Methodology, such as by Hubka (1982), Pahl and Beitz (1996), Cross (2000), Pugh (1991), Ulrich and Eppinger (1995) or French (1999); a further list of contributions have been noted by Cross (1993). The common thread across these is the agreement that design is an iterative process of activities performed and decisions taken across several, overlapping stages, and that the use of design methods "brings rational procedures" (Cross, 2000) into the design process. Several other studies, however, found that relatively few methods were widely and systematically used, with many methods adapted using ad hoc modifications and abandoned mid-way into the design process (Lopez-Mesa, 2003). More recently, Chakrabarti and Lindemann (2016) reported, based on results from large-scale studies across industry, that the correct use of appropriate design methods and tools resulted in significant positive impact on industrial practice; use of design methods and tools not only systematized the process but also improved the design outcome. The appropriate selection of methods was found to be a key factor for successful use of methods (Ritzén and Lindahl, 2001; Ernzer and Birkhofer, 2002).

Web-based portals, such as "Pinngate" (Sauer *et al*., 2006), and computer-based tools, such as Competence in Design and Development "CiDaD" (Ponn and Lindemann, 2006) and Landscape of Methods (Strasser and Grösel, 2004), have been developed to support the use of design methods in practice. Other more recent, web-based design supports include the Design Exchange (Roschuni *et al*., 2011, 2015), the Amsterdam mediaLAB Design Method Toolkit (Amsterdam, MediaLab., 2016), the IDEO Designkit (Kelley *et al*., 2013), WikID by Industrial Design Engineering at TU Delft (Vroom and Horváth, 2014), the Korea University Design Method Toolkit (KIID, 2014), the Google Design Sprint Kit (Banfield *et al*., 2015), Design and Emotion Society Library (McDonagh *et al*., 2004), Usability.gov and Usability Body of Knowledge (Usability Professionals' Association, 2005). Most of these are databases tagged to design stages or micro-cycles, with descriptions and categorizations, but with little clarity on the specific improvement about in the design outcome as a result of use of these methods. Tools such as mind-mapping or Idea-Inspire (Chakrabarti, *et al*., 2005), on the other hand, focus on specific improvements (e.g. design synthesis) but are not integrated within the design stages or life cycle. What is ideally needed is a combination of both, as discussed in the section "Discussion and inferences from the literature".

Discussion and inferences from the literature

The above review of literature indicates two major needs. The first is the need for inculcating life cycle thinking for design for sustainability (DfS). The second is the need for following a systematic design process that integrates the selection and use of appropriate methods and tools during the process. However, these two strands of research have rarely been brought together. In order to address this gap, the work reported in this paper proposes a support tool with the following requirements:

1. *Integration* of life cycle thinking within a systematic design process;
2. *Selection of appropriate methods*, with respect to the contexts and benefits of use; and
3. *Appropriate use of the selected methods*, with clear instructions on their procedure from defined start to desired end points, as well as the clarification of resources and training needed as a prerequisite to their use.

The support tool is expected to provide an integrated platform that would allow movement through design stages and activities, supported by appropriate methods and tools, to reduce the cognitive burden on designers.

Research framework and methodology

Ontological framework for organizing design knowledge

InDeaTe has been developed based on an empirically validated, holistic design framework – ACLODS (Kota and Chakrabarti, 2014). ACLODS is an acronym for design dimensions, namely, *A*ctivities, *C*riteria, *L*ife cycle phases, *O*utcomes, *D*esign stages, and *S*tructure. These dimensions, variously reflected in design methodologies and observed across empirical studies, have been found to be consistent and essential for designing the life cycle of a system (Kota and Chakrabarti, 2014). The dimensions are defined as follows;

Activities are performed during the design process on the Outcomes (see below); the activities used in InDeaTe are: Generate (G), Evaluate (E), Modify (M), and Select (S).

Criteria are considerations for a design. For DfS, the key criterion is sustainability, which can be described using the TBL, that is, sustainability dimensions of the environment, society and economy (Elkington, 1997), and can be quantified using appropriate indicators.

Life cycle phases of a design are the contributors to the sustainability of the system being designed. The phases consist of processes, where each process impacts the ecology, economy, and society, influencing their sustainability. The phases are Materials (Mat), Production or Manufacturing (Mfg), Distribution, Storage and Transportation (Dist), Use (Use), and After-Use (AUse).

Outcomes of design are either *requirements*, that is, what needs to be satisfied by the system being designed (needs, demands, or wishes to be fulfilled by the system), or *solutions*, that is, how the requirements could be fulfilled, at different levels of abstraction from concept to embodiment. These outcomes, driven by the criteria, emerge and co-evolve through the stages of design.

Design stages are the four broad temporal divisions within the design process, Task Clarification, Conceptual Design, Embodiment Design, and Detail Design, as prescribed in many design methodologies such as Pahl and Beitz (1996). Each stage has well-defined deliverables that act as input for the next stage.

Structure of a design are the entities that the designer conceptualizes and embodies during the design process. In products and manufacturing systems, structure is often associated with a set of physical objects; empirical studies, however, reveal that an abstract structure exists even at the conceptual stage (Acharya and Chakrabarti, 2017).

The ACLODS (Kota and Chakrabarti, 2014) ontology supports the uniform representation of all design-related information available in the database of the tool proposed, so that this information can be utilized in appropriate contexts within the design process.

Methodology for the assessment of the effectiveness of InDeaTe tool

For assessing the effectiveness of InDeaTe, a series of design exercises were conducted. The design concepts developed in the exercises were compared by experts or clients for improvement in sustainability and with additional user feedback collected via questionnaire on other aspects of the design process. The effectiveness of the tool was assessed against the following criteria:

(i) Number of requirements generated and percentage of sustainable requirements within these;
(ii) Number of solutions generated, percentage of sustainable solutions among these, and percentage of sustainable solutions selected among the total generated as final concepts;
(iii) Number of sustainability Definitions and Principles selected;
(iv) Number of sustainability Indicators selected and percentage considered or used in generating requirements;
(v) Number of Design Methods and Tools selected in all stages of the design process, and percentage considered or used in the design process.

The rationale for using the above criteria is the following criteria. Criteria (i) & (ii) should help assess improvements in sustainability considerations due to the use of InDeaTe tool; while Criteria (iii), (iv), & (v) should help assess the contribution of the various types of knowledge provided by the InDeaTe tool during the design process. It is the percentage of use of this knowledge in the design process, as opposed to the knowledge initially selected from the tool, that reflects the efficiency of the tool in supporting the design of sustainable systems.

Description of the InDeaTe tool

InDeaTe is a computer-based tool developed for supporting the design of sustainable products, manufacturing, and service systems. It approaches design process holistically – from problem identification and solution seeking, through concept selection and detailing, to the development of documents – all critical to design practice. The tool has two modules: a generic design process *Template* (section "Ontological framework for organizing design knowledge") that imbibes life cycle thinking into the design process and a *Design Database* (section "Methodology for the assessment of effectiveness of InDeaTe tool") of sustainability Definitions, Principles and Indicators (SDPI), as well as design methods and tools, all ontologically tagged using the dimensions of ACLODS.

The three main functionalities of the tool are as follows:

(i) to *provide knowledge on sustainable design* as a process provided by the Template by training the user with ACLODS as an ontology for tagging of its database; and on sustainability definitions and measures, and design methods and tools provided in its database;

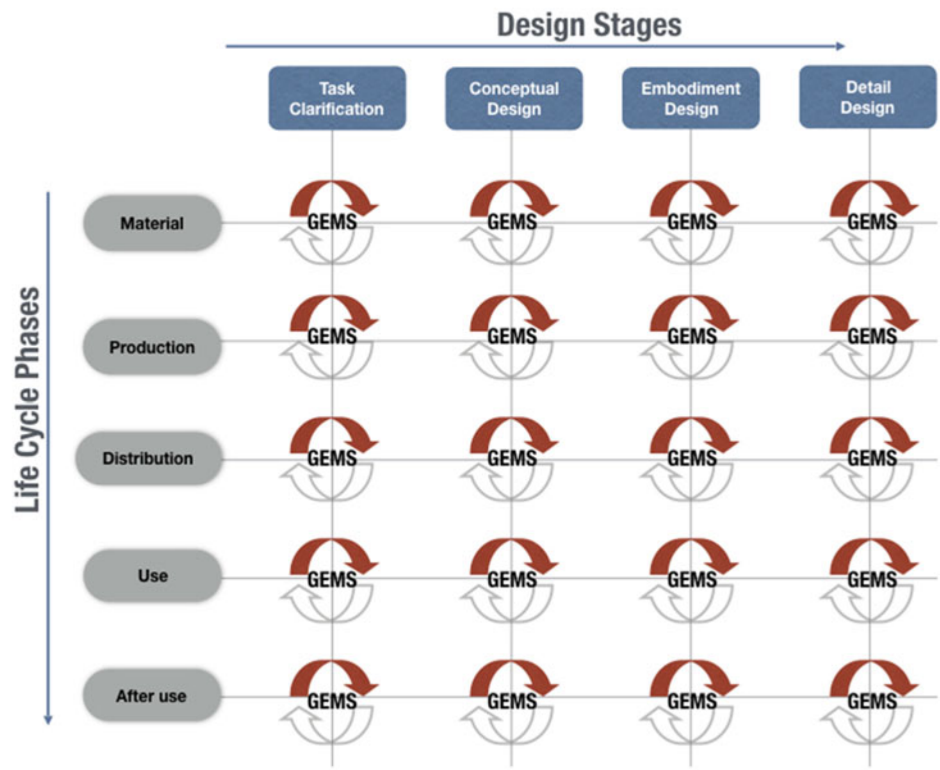

Fig. 1. InDeaTe design process template.

(ii) to *support the on-going design process* through pertinent, ontologically tagged information and aid in performing design activities with the use of appropriate methods and tools from the database; and

(iii) to *support design research and retrospection* on the design process by creating design documents that captures the decisions and rationale of a project.

InDeaTe is envisioned as a web-based, open-source support with a crowd-sourced, expandable repository.

InDeaTe design process template

The InDeaTe design process Template is generic in its applicability across several types of systems and domains. It supports life cycle thinking at the intersections of life cycle phases (L) and the stages of design (D) and prompts iterative design Activities (A) for sustainability as Criterion (C). Figure 1 illustrates these intersections in the process that guides the formulation of requirements and solutions, that is, Outcomes (O) that are further developed into concepts and embodiments, that is, Structure (S) that are more sustainable. The template recommends steps or guidelines, outlined in Table 1, which direct the design activities and guide the use of the database.

InDeaTe Design Database

The Design Database in InDeaTe supports the design process with "sustainability Definition, Principles and Indicators" (SDPI) information to help clarify the design intent, in terms of the aspects of sustainability of the system to be improved; and the "methods and tools" information for its appropriate selection and use to perform the iterative activities. The database is organized with respect to the dimensions of sustainability, that is, Triple Bottom Line (TBL) (Elkington, 1997) and the ACLODS ontology (Kota and Chakrabarti, 2014), so that relevant information can be easily accessed, understood, and used. This allows filtering of information from the database to the designers, as per the sustainability goals and the focus of the system being designed. The comprehensive list of sustainability definitions and principles in the InDeaTe database helps represent the generic sustainable development perspectives of the design project through the selection of one or more of these to guide the design process. The sustainability indicators in the database are specific measures for the selected definitions and principles that aid help evaluation for decision-making.

The design methods and tools database aids in the appropriate selection of methods and tools for the specific Activities, Life cycle phases, and Stages during the design process. The database also aids the designers in the appropriate use of the methods and tools selected.

User-interface and working of InDeaTe

InDeaTe guides a design project using its generic process Template and its recommended steps, see Table 1. As the project progresses from task clarification to conceptual design and so on, the designer searches the databases in the prescribed steps to identify appropriate sustainability definitions, principles, and indicators for the generation of requirements. Pertinent design methods and tools, filtered against the designer's selection of problem type, TBL scope, Life cycle phase, design stage, and design activity, are suggested by the tool to aid the design process. The tool provides an input–output representation for each method/tool, along with its objectives, structure or means of use, requirements, benefits, and costs. Furthermore, each method is linked to case studies that act as examples of the contexts and use of the methods. The steps followed and the design

Table 1. Steps of the InDeaTe design process template

Design stages	Step no.	InDeaTe template: design process steps	Deliverables
Task Clarification	1	Select system boundary	1. Preliminary list of requirements often qualitative with some understanding of their relative importance, often qualitative.
	2	Analyse current situation to identify issues (Generate Requirement)	
	3	Using the tool/database select Sustainability Definitions and Indicators to be used in the process	2. Some ideas of how to solve the design problem, noted down for further use.
	4	Evaluate the issues to find the important ones to address (Evaluate/Modify Requirements)	
	5	Decide on a list of requirements and their relative importance for use the subsequent stages (Select Requirement)	
Conceptual Design	6	Generate alternative ideas to satisfy each major requirement (Generate Solution)	1. A more concrete list of requirements.
	7	Evaluate these ideas to select the most promising ones (Evaluate/ Modify Solution)	2. A list of possible solution-variants that could be used to solve the problem (i.e. satisfy these requirements).
	8	Integrate these ideas to generate alternative solution principles (Generate/Modify Solution)	3. An evaluation of these variants for their suitability to satisfy these requirements.
	9	Evaluate these alternatives to select the most promising solution principle (Evaluate/Select Solution)	4. The solution-principle selected as the most promising for further development.
Embodiment Design	10	Develop alternative, concrete configurations of the sub-systems/ parts for the solution principle chosen in CD (Generate Solution): How can each subsystem/part of the solution principle be embodied? What are the other ways it can be embodied?	1. A more concrete list of requirements. 2. A list of possible solution feasible configurations that could be used to embody the solution-principle.
	11	Evaluate and select among these alternatives based on their suitability (Evaluate/Select Solution): Will the alternatives satisfy the (refined list of) requirements? Can these be tested via calculation, virtual simulation, or physical simulation?	
	12	Integrate these to generate alternative solution-embodiments (Generate/Modify Solution): Which embodiments of these concepts can be developed into complete configurations? Are additional elements needed to put these together?	
	13	Evaluate these alternatives to select the most promising solution-embodiment (Evaluate/Select Solution): Which of the combinations best satisfy the requirements? Which of these is the most feasible?	
Detailed Design		*This stage begins with the deliverables from ED and ends with a more concrete and finalised list of requirements; a list of possible optimized solution configurations for the chosen embodiment from ED; an evaluation of these configurations for their suitability to satisfy the requirements; and a specification of the optimized configuration selected as the final design ready for implementation. This stage typically requires a large amount of domain-specific information and therefore is left out from the generic recommendation that is proposed under the InDeaTe template.*	

information used are automatically recorded as the tool is used, thereby providing a documentation of the process chosen to be carried out.

Case studies

To assess the effectiveness of InDeaTe, six comparative design case studies, each with two outcomes – one with and the other without the use of InDeaTe, were undertaken. In the studies where design sessions "without use of InDeaTe" cases were unavailable, design outcomes from the session using the tool were compared with the existing designs. The effectiveness of the tool was evaluated by analyzing the re-designed outcomes with respect to the satisfaction of requirements and the improvement of sustainability considerations by users or clients, and by assessing the application of the tool through retrospective questionnaire answered, by the participants in the design teams in these studies, on their experience of using the tool, see Criteria (i)–(v) in the section "Research framework and methodology".

Two empirical design sessions with three case studies each were conducted in June and October 2015, in India and USA, respectively, with design teams comprising students from both the countries. Each case study was on one of three types of design problems – products, manufacturing systems, or service systems – with the intent of improving the sustainability of an existing design. The deliverables of each study were the iterative list of requirements generated, sketches of solution, concept selected and embodied, documentation of the design methods and tools used, and answers on retrospective questionnaire. The teams designing with the use of InDeaTe tool used both the step-by-step template prescribed in Table 1 and the design database discussed in the section "InDeaTe design database". Thus, each session included introduction of the problem brief and tool to the team concerned, the design exercise spanning several days and across various stages of design as time permitted, and evaluation of the effectiveness of the tool.

Case study session 1 with InDeaTe v1.0 in India

The three re-design problems for empirical study were identified from existing and in-use design solutions in India. Designs conferred as innovative were selected and the problem brief designed by members of the National Innovation Foundation (NIF) India who had worked closely with the innovators of these solutions. Each problem description, along with details of the associated empirical study (team composition, duration of study, design stages addressed) is elaborated in Table 2.

The main findings and observations from the first study are the following:

- Use of InDeaTe expanded existing concept space and resulted in the generation of a larger number of feasible solutions.
- Use of InDeaTe improved sustainability considerations in the solutions; the re-designed solutions systematically incorporated a number of sustainability strategies.
- Teams appreciated the structure and resource accessibility of the tool.
- A lack of training and time for understanding the template and in clarity on how to use the database were observed.
- A trend in designers using certain methods with which they were already well versed was observed.

Therefore, the key areas of improvement, leading to development of InDeaTe v2.0, were identified as follows:

- Expand the database with more methods and tools for supporting different scenarios;
- Add information on time and skill requirement for use, and domains of application;

Table 2. Design exercises

Tool version	Type of design	Problem brief	Participants	Exercise duration
InDeaTe v1.0	Product	(Ghadge *et al.*, 2017*a*) *This case study describes the re-design of a natural water cooler not requiring electrical power and is low in maintenance, cost, and is suitable for public use.*	Team 1 (with the tool): 3 students – 2 PhD students – 1 from India, 1 from USA, and 1 UG student from India. Team 2 (without the tool): 4 students – 3 PhD students – 2 from India and 1 from the USA, and 1 UG student from India.	No. of days: 2 No. of hours: 16 Stages of design addressed: • Task Clarification • Conceptual Design • Embodiment Design
InDeaTe v1.0	Manufacturing System	(Ghadge *et al.*, 2017*b*) *This case study describes the re-design of an innovative micro-hydel power system of 1–10 kVA capacity installed in the hills of Karnataka.*		No. of days: 2 No. of hours: 16 Stages of design addressed: • Task Clarification • Conceptual Design • Embodiment Design
InDeaTe v1.0	Service System	(Devadula *et al.*, 2017) *This case study describes the re-design of a network of community workshops all over India to improve the technical problem solving and prototyping activities of the local populations for supporting grassroots innovations.*		No. of days: 2 No. of hours: 16 Stages of design addressed: • Task Clarification • Conceptual Design
InDeaTe v2.0	Product	(Acharya *et al.*, 2017*a*) *This case study describes the design of a product for replacing the current manual process of manufacturing wood-based boards at the Composite Materials and Engineering Centre, Washington State University, Pullman.*	Team 1 (with the tool): 3 PhD students – 2 from India and 1 from the USA.	No. of days: 4 No. of hours: 35 Stages of design addressed: • Task Clarification • Conceptual Design • Embodiment Design
InDeaTe v2.0	Manufacturing System	(Uchil *et al.*, 2017) *This case study describes the design of a "smart" manufacturing line for an automated machine shop for making a given shaft, meeting the following requirements:* (a) *Easy market adoption* (b) *Charging station* (c) *Faults, failures, and manufacturing issues*	Team 1 (without the tool): 2 PhD students – both from India, Team 2 (using the tool): 2 PhD students – 1 from India and the other from the USA.	No. of days: 4 No. of hours: 32 Stages of design addressed: • Task Clarification • Conceptual Design
InDeaTe v2.0	Service System	(Acharya *et al.*, 2017*b*) *This case study describes the re-design of a green-roof for Syracuse city that will store stormwater of a strong storm for an adequate time so that the capacity of Metro would not be exceeded.*	Team (with the tool): 3 PhD students from India and 3 PhD students from the USA	No. of days: 5 No. of hours: 40 Stages of design addressed: • Task Clarification • Conceptual Design

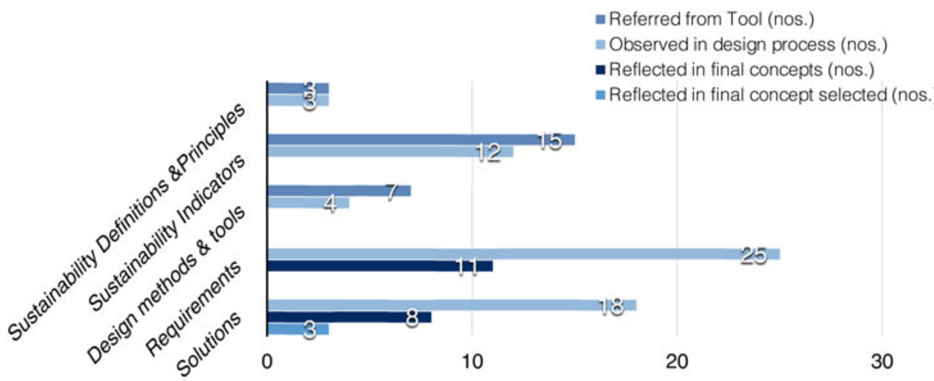

Fig. 2. Design data with use of the InDeaTe tool (product design of OS board-making unit).

- Develop training material on the use of InDeaTe template and databases;
- Improve the UI of the tool to support intuitive navigation.

Case study session 2 with InDeaTe v2.0 in the USA

A second study was conducted, in October 2015, to assess the effectiveness of InDeaTe v2.0, to assess its improvements above and its applicability in a different geo-cultural context. Three design problems relevant in the USA, outlined in Table 2, all with existing solutions, were selected for re-design aimed at improving their sustainability.

The main findings and observations are the following:

- Use of InDeaTe tool improved the existing concept space, in agreement with results from the first study.
- Use of InDeaTe tool improved the sustainability considerations in the re-designed solutions compared to the existing designs used as benchmark, also in agreement with results from the first study.
- Teams continued to appreciate the structure and resource accessibility of the tool.
- The presence of a team member well versed with the tool and template allowed smooth navigation of the design process and the computer-based tool.
- The trend of designers using certain methods with which they were already well versed continued, but the method representation newly incorporated was found helpful for selection of methods.
- The UI of InDeaTe v2.0 was found to be easy for referencing the template and the database.

Overall results from the empirical studies

The design data, collated from the design processes in the series of exercises at the USA, for assessing the effectiveness of InDeaTe, as illustrated by the example in Figure 2, highlights its influence on the design outcomes. The tool not only contributes towards consideration of design knowledge, but also to its application in the design process, across the various types of systems, as seen in Figure 3.

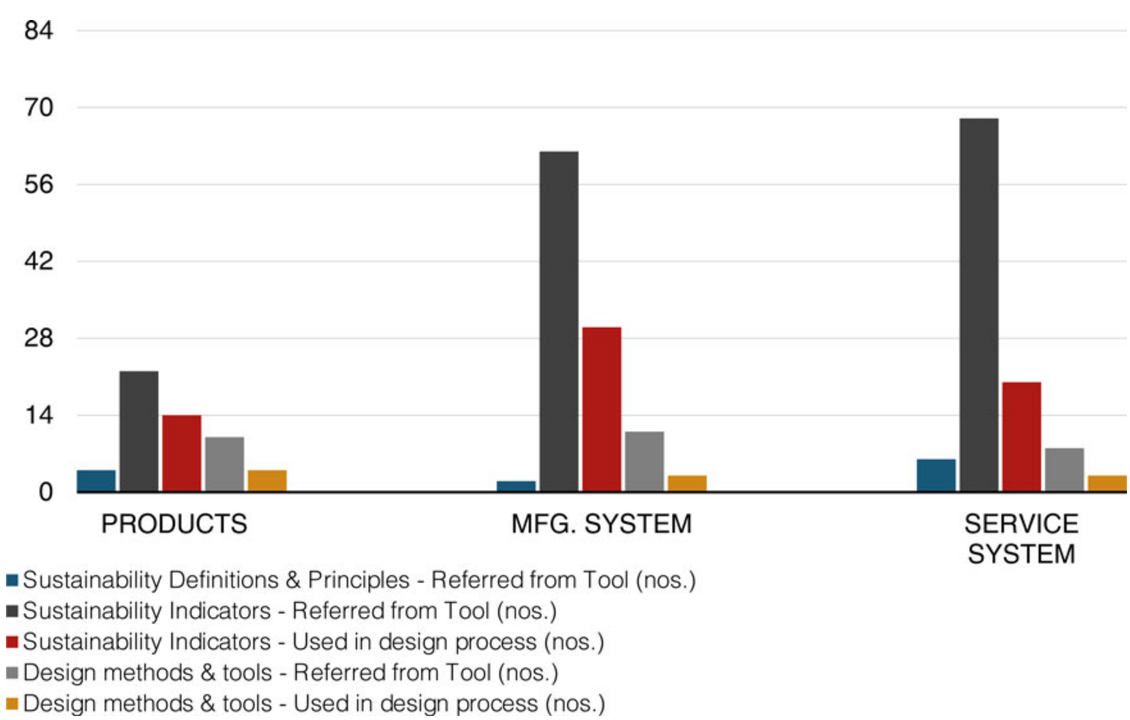

Fig. 3. Percolation of design knowledge by use of the InDeaTe tool across re-designed systems.

The criteria discussed in the section "Methodology for assessment of effectiveness of InDeaTe tool" have been used to analyze the design exercises with the following results:.

i. The percentage of sustainable requirements out of the total number of requirements generated, as observed with the use of the tool, was within the range of 40%–45%. This elucidates the influence of the tool in improving the consideration of sustainability through the development of sustainable requirements.
ii. The percentage of sustainable solutions amongst the total number of solutions generated was within the range of 40%–50%; while it dipped to below 40% in the final concept selected. This indicates that the tool also enables the incorporation of sustainability into the resulting design.
iii. The number of Sustainability Definitions and Principles selected from the tool were between two and five in number, with mostly a common set for each type of system to be designed. The number of selections in itself did not confer any evidence towards the effectiveness of the tool. However, these selections translate into a set of filtered Indicators, and a complementary relationship was observed between the percentage of consideration of sustainability indicators and the generation of sustainability requirements.
iv. The percentage of Sustainability Indicators considered or used in generating requirements (Fig. 2) was high, with up to 80% of the total referred from the tool. In spite of the comparative availability of pertinent sustainability indicators being fewer in product design (Fig. 3), as opposed to those for manufacturing or service systems, the percentage of its percolation into the design process and its eventual outcome, that is, 63.6%, was the highest. The provision of sustainability Indicators by the tool reflects on the positive effect of this knowledge, of impact, and its measure, in improving design through the development of requirements to be addressed.
v. Similarly, up to 40% of the design methods and tools selected from the InDeaTe database was observed to have been used in the design process for products, and a similar value of 37% in services. However, the lowest of 27.3% of use of design methods in the process was observed for manufacturing systems. The use methods and tools in the design process indicates the current capability of the tool to support the design of systems and implies the need of further investigation.

Summary and conclusions

Design is a vehicle for sustainable development. Life cycle thinking is an important instrument with which sustainability considerations can be imbibed into a design, while using appropriate tools and methods to aid designers perform design activities in each design stage to achieve specific goals. The novelty of the InDeaTe tool lies in its integration of the life cycle phases of a design within each stage of design and its supports for carrying each design stage with relevant design methods and tools that are integrated to the template through its two design databases. Two versions of InDeaTe have been empirically tested, where comparative analysis of the effectiveness of InDeaTe has been evaluated with respect to five assessment criteria using six case studies. The results indicate that the InDeaTe tool has the potential to support a systematic design process and aid in the successful incorporation of sustainability considerations across its multiple dimensions through solution development. The use of InDeaTe offered the design teams a structured process for design and resulted in the development of comprehensive lists of requirements and in turn, in the generation of a large number of solutions. Also, the use of tool reflected positively on the percolation of design knowledge with respect to sustainability indicators to clarify intent and in use of design methods and tools to perform the design process. It may be concluded, therefore, that InDeaTe promises to be an effective tool for DfS, as it seems to have holistically supported different aspects of design – the design approach, the design intent, and design methods and tools for different types of systems.

Limitations and future work

While the findings in section "Summary and conclusions" indicate promise for InDeaTe, a number of areas need further improvement, validation, and expansion, as outlined below.

Across the case studies conducted, a major limitation has been the potential lack of uniformity among teams, with respect to the participants' education, prior experience, knowledge and design vocation, as well as time spent across the design sessions. Hence, a more comprehensive testing of InDeaTe needs to be carried out, in realistic scenarios across diverse users and clients.

While literature reports a large number of methods and tools for supporting DfS, empirical verification is seldom reported for the underlying design models on which the methods are based, or for the prescriptive efficacy of the methods. Future work includes documenting real-time use of the tool and user feedback through crowd-sourcing on the use and usefulness of the methods and tools, so as to provide detailed validation of its effectiveness.

Finally, though sustainability is the key criterion for which InDeaTe has currently been tested, it may have potential for supporting design-led innovation in general. This too requires further development and validation.

InDeaTe is envisioned as a support that would dynamically grow with the user addition of information, knowledge, and feedback, so as to eventually support both design and design research.

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