Supporting Manufacturing System Design: A Case Study on Application of InDeaTe Design Tool for a Smart Manufacturing System Design

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Abstract InDeaTe is a Design Tool that aids the designer by empowering ideation through a methodical process of design. This paper presents the evaluation of the tool through a case study on a manufacturing system design problem conducted in University of California, Berkeley. The problem given was to design a 'smart' manufacturing line for a lawnmower shaft. Four designers participated in the exercise, in teams of two each; one team used the tool and other did not. Design outcomes were compared. Analysis of the results showed a larger number of ideas generated by the team using the tool compared to the team without the tool. This study, although conducted over a short period with limited number of designers, illustrates the potential of the InDeaTe tool to address manufacturing system design problems by not only developing a richer subset of design outcomes, but also by taking into account sustainability considerations throughout the product life cycle.

Keywords Smart manufacturing · Design for sustainability · Enabling technologies and tools · InDeaTe tool

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1 Introduction

This paper describes a case study conducted to systematically evaluate the influence of following a structured design process and methods using InDeaTe tool than without using the same. Structure of the paper is as follows. Section 1.1 provides motivation behind choosing smart manufacturing system design as the problem domain, Sect. 2 introduces the research objectives and the problem brief, Sect. 3 introduces the InDeaTe tool; describes design exercise carried out using the InDeaTe tool and without using the InDeaTe tool, Sect. 4 includes analysis of design process, Sect. 5 covers evaluation of the outcomes of the exercise, Sect. 6 summarizes the work and reflects on the effect of the InDeaTe tool.

1.1 Focus on Smart Manufacturing System Design Problem

With ever increasing tension between consumer demands and natural as well as engineered resource depletion, some of the most advanced economies are seeking to revolutionize their manufacturing competencies through smart manufacturing [1]. Such blending of the physical and cyber worlds is expected to open up doors for innovation that has the potential to optimize the entire manufacturing sector to improve quality, flexibility, productivity, and energy efficiency without compromising on sustainability. The National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce, and a strategic leader in this area defines Smart Manufacturing as systems that are "fully-integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs [2]. Realization of smart manufacturing involves the integration of several technologies such as the Internet of Things, big data analytics, multi-scale dynamic modelling and simulation, networked sensors, Cloud computing, 3D printing, smart factories, smart grids, interactive visualization, data interoperability, and scalable multi-level cyber security [3].

This case study was conducted at the Laboratory for Manufacturing and Sustainability (LMAS), University of California, Berkeley. Smart manufacturing research at LMAS focuses on big data analytics [4] and data harnessing from advanced sensor systems [5].

2 Research Objective and Methodology

The research objective is to evaluate InDeaTe tool through a case study on a manufacturing system design problem. The research methodology included a series of design experiments to evaluate the effectiveness of InDeaTe on a broad set of problems that includes product design, manufacturing system design, and service system design. These problems were attempted with and without using the tool by different teams, and the process and results compared for assessment of tool efficacy.

2.1 Problem Statement

The problem statement, provided by LMAS, is as follows: the transmission shaft of a particular lawnmower is manufactured by three different processes, on three different machines, in the following sequence: CNC Turning, CNC Milling/Drilling, and Grinding. The participants were asked to Design a ‘smart’ manufacturing line for an automated machine shop for making this shaft. The machine tools have several sources of data, and many of these data sources are wireless sensors which run on batteries. The manufacturing line should meet the following requirements.

(a) Easy market adoption—how can an existing manufacturing line be converted into a ‘smart’ manufacturing line without revamping the locations of all of the machines?
(b) Charging station—Wireless sensors running on batteries need to be charged regularly. What is the minimum battery life needed so as to be unobtrusive in an existing manufacturing line? How can this be made easier? How can the charging of sensors be made effortless and easy in the manufacturing environment?
    Faults, failures, and manufacturing issues, what does a revamped manufacturing line look like? What are the activities that still have to be performed manually? What skill levels change? Are smart phones needed for monitoring and is that something that can be adopted today?

3 Design Exercise

The design exercise started with an introduction to the design problem. The exercise was conducted with two teams—one using the InDeaTe tool and the other without using the tool. The outcomes from the two design exercises were then compared. Each design exercise lasted approximately 32 h, spread over four days. The InDeaTe tool is described below, followed by the process and outcomes of the design sessions carried out without and with using the tool.

3.1 InDeaTe Tool

The InDeaTe Tool is a knowledge-driven support for designing sustainable products, services and manufacturing systems. It comprises a design process *template* and a database that work together with a *database* of methods and tools, to support the designers through a computer interface. The template is derived from the ACLODS framework [6], which presents a new paradigm of design in terms of the following dimensions: Activities, Criteria, Lifecycle phase, Outcomes, Design Stage and Structure. The tool introduces the user to some of these dimensions—Activities, Lifecycle phase and Design Stage—before prescribing the Template. The template offers an overview of the design process and provides a generic guideline to follow during the design process. Four stages of design are prescribed—Task Clarification, Conceptual Design, Embodiment Design and Detail Design [7]. Every design has up to five Life cycle phases: Material extraction, Production, Distribution, Use and After Use. The Template encourages designing for the entire lifecycle of the product, with the aim of making it more sustainable.

3.2 Solution Without Tool

3.2.1 Task Clarification

As a review of the design problem indicated multiple issues at system level, designers felt it necessary to identify significant issues that could be realistically addressed within the limited time and resources. Among all the sources of information available, eliciting information from domain experts were considered to be quicker and relevant as experts, having worked on various aspects of the problem at level of systems and subsystems, should be able to provide inputs that would serve in narrowing down the area of focus.

3.2.2 Use of Expert Interview for Task Clarification

Through an expert interview, it was inferred that charging sensors was the most significant issue. Given the resource and team constraint team felt it would be worth addressing one issue in detail instead of attempting to different subsystem of the problem. Therefore, the team decided to focus on addressing the issue of charging. In order to direct the design effort only on the charging issue, the modified problem statement deliberately excluded the other chunks of the problem that did not have a relationship with the issue of charging. In order to have a larger solution space, the problem statement was abstracted and defined in a way that potentially avoided any early design fixation.

An important step in the problem solving approach was defining the problem in a solution neutral way Pahl and Beitz [7], something that the designers involved had learnt from their masters level product design courses. An underlying objective behind this approach was to define the problem at an abstract level without being committed to any particular solution. For instance, defining the problem as “designing a charging device for sensors” could potentially fixate the solution space to the electrical domain through the word “charging”, which would reduce the search for new ideas from an another domains such as biology or archaeology.

3.2.3 Solution Neutral Problem Statement

Design an unobtrusive, easy to use, energy transfer device

3.2.4 Idea Generation and Conceptual Design

For solution space generation, one of the methods used was bio-mimicry. The designers employed this methodology using Ask-Nature [8] as the source of information. Ideas generated included sensors that would work on number of solution principles such as (a) converting thermal energy produced from heat dissipation from the tools to electrical energy (b) using generator coils around rotating elements to harness energy; (c) using power from electrical supplies provided for the machine itself; (d) using photovoltaic coatings on bearing surfaces; (e) using light harvesting nano-structures, and (f) using noise to generate energy.

3.2.5 Detailed Design

Concept selection was done using relative weighing of concepts and with a review by experts with respect to energy efficiency and ease of market adaption. The final selected concept included systems that harnessed energy from vibrations and sound and converted these to electrical energy.

3.2.6 Design of Sensor Network Interface Architecture

For a manufacturing system, the engineers using the system needed continual indication on the energy level and the spatial location of the sensors in the system. This is accomplished by a dashboard with a modular architecture that is compatible across various devices such as digital monitors in machine control rooms, laptops and mobile devices. Figure 1 shows the on-site monitoring system via a mini-dash, available as a device or an app on a smart phone/pad, with the basic information required for repair, service and calibration. This minimised the need for high level of skills for the labour required. The proposed automatic turn-off mechanism of the sensor through control switches was expected to improve energy efficiency through avoiding charge run off.

3.3 Solution Using the Tool

The team using the tool followed the steps described in its template which starts with the Task clarification stage.

3.3.1 Task Clarification Task clarification begins with identifying the system boundary to scope out the problems beyond the purview of the design. This step is

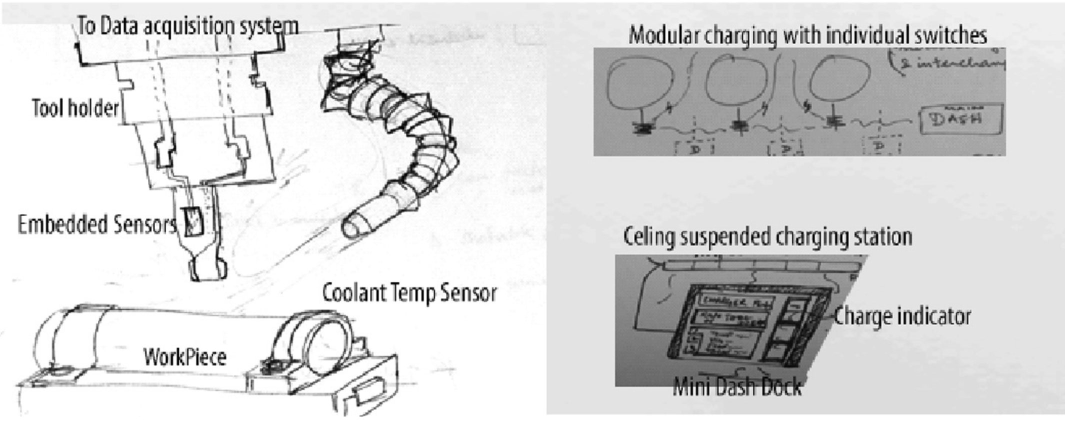

Fig. 1 Proposed configuration of a sensor charging system and interface

followed by describing the issues within the system boundary, followed by identifying the stakeholders with an influence on the problem, and identifying the flow of work through flow analysis. In the following paragraphs we describe the outcomes of carrying out these steps.

3.3.2 System Boundary Manufacturing processes that were not allowed to be changed were CNC Turning, CNC Milling/Drilling and grinding on different machines. The variables identified were interactions among between the machines, activities performed by the operators, data collected and used, and decisions automated.

3.3.3 The Issues identified after analysis of the current situation were as follows: Manual monitoring of machines and processes; bad quality production due to degraded cutting tools; downtime due to (a) maintenance (b) tool failure (c) non-availability of operator, and (d) non-availability of appropriate materials.

3.3.4 The Definition of sustainability used was from the U.S. Department of Commerce. It defines Sustainable manufacturing as 'creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers.' The methods shortlisted for identifying requirements were Stakeholder mapping, House of Quality, Flow analysis and 6R.

3.3.5 Stakeholders were identified were: Organisation, Employees (operator, line manager, shop supervisor, upper management), suppliers, clients/customers, and transporters.

3.3.6 Flow Analysis Identification of life cycle processes and mapping of material flow has been carried out to chart out critical processes and activities that govern manufacturing system. A preliminary conceptual map of material flow as, has been constructed starting embracing life cycle thinking concept. We acknowledge that the Figure is missing essential quantitative material and energy flow information to be termed as material flow analysis diagram. We are currently imitated by lack of quantitative data at early state of design, such as amount of material flow or energy consumption to generate detailed material flow diagram.

3.3.7 List of Requirements All these steps helped in clarifying the design requirements and defining the problem precisely. Each requirement was categorised into a demand or a wish. The demands were the following: automated monitoring of machines and tools, easy Charging of sensors, minimize downtime, and minimize rework or reject components, ensure safe working environment, and avoid bottlenecks between sequential processes.

Wishes considered were the following: automated tool change after tool failure, indication of optimum tool changing time, minimize coolant use, minimize scrap generation, minimize quality checking (or automate it), easy market adoption.

3.3.8 Solution Neutral Problem Statement 'A manufacturing line that optimises production and minimizes resource consumption while ensuring quality, ease of maintenance and good labour practices.'

3.3.9 Conceptual Design The conceptual design stage determines the principle solution for a given problem. After task clarification, brainstorming was done for each requirement. Using the ideas generated during brainstorming, Morphological charts were used to generate solution variants. The requirements were compared with each other to identify their relative importance, denoted by their weighing factors. Then the solution variants were evaluated for each requirement using weighted objectives method and scores were calculated. The variant with the best score was chosen as the concept.

4 Analysis of Design Processes

During the task clarification phase designers were frequently referring to the InDeaTe tool for following the systematic design process and identifying information related to the each process. The design team using the tool was not particular about the definition, as long as it covered the triple bottom line. Sustainability indicators, although not used while solving the given design problem, gave pointers for identifying a comprehensive set of requirements. Due to scarcity of information available about the design, environmental behaviour of the proposed design throughout its life cycle could not be precisely described.

Brainstorming was carried out for each requirement. Morphological charts were made for combining the ideas generated during brainstorming. However, the ideas in each row of the chart were not independent to one another. There were overlaps between some ideas in the same row.

The Weighted objective method was used for selecting the best concept from among the solution variants. The outcomes of the Team using the tool were reported in a tabular or textual form. This is not a shortcoming of the tool. Since one of the team members was working in the same research area, there could have been some bias, either good or bad. The Morphological charts method was used because of familiarity and ease of application within the time constraint, but better methods were desired.

5 Evaluation of the Exercise with the Template and Without the Template

The objective of the evaluation was to compare the effectiveness of outcomes generated using the template to those without using the template. In order to minimize the influence of domain knowledge, it was assumed that designers had a similar magnitude of training and experience in design related domain. Considering the similar backgrounds of individual designers having masters in design related domain; an experience of 1–2 years was taken to be safe assumption to make. As there were no explicit benchmark for assessing the "quality of the solution" as the problem itself was new, the "number of ideas generated" has been used as a measure of the effectiveness of the outcome.

Analysis of the design documents showed that the number of ideas generated using the tool was 69 and without the tool were 14. The difference may be due to observation that the designers using tool used several methods and hence they might have had more perspectives to analyse the problem that resulted in a larger number of ideas.

However, current measure of effectiveness was limited by the lack of concrete benchmarks for assessing the effectiveness of solution-development methods at the early state of design (Fig. 2).

In order to evaluate the quality of the ideas, we have used multi criteria evaluation method and outcomes are presented in Table 1. The criteria for evaluation are based on the list of requirements mentioned in Sect. 3.3.7. The criteria used are

(a) 'Ease of charging' is described in terms of 'time taken for charging' and 'perceived simplicity of charging system'.

    (i) 'Perceived Time taken for charging' is assessed by energy transfer rate of a technology under consideration. Rating range between 1 and 5, 1 being fastest, 5 being slowest with "Less is better approach". For example an

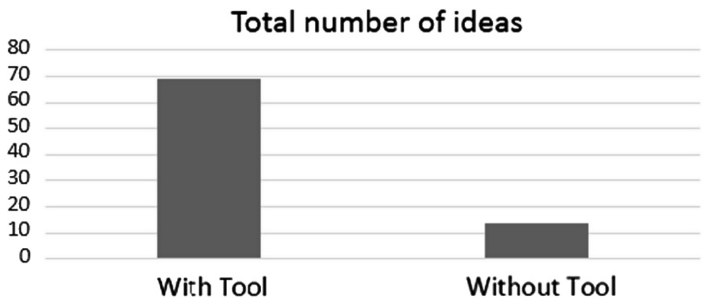

Fig. 2 Number of ideas using the template and without using the template

idea that comprises wired energy transfer has been rated lower than wireless energy transfer technology on the assumption wired technologies can transfer faster than wireless.
(ii) 'Perceived simplicity of charging system' is assessed by likely number of components present in the system. For example: an idea that comprises wired energy transfer is assumed to have more number of components and hence rated higher than wireless counterpart.

(b) 'Perceived Energy efficiency' is assessed by potential of an idea to reuse the energy from the system itself instead of using new source of energy.
(c) 'Novelty' is assessed through score of 3. Score of 1 indicates 'low novelty idea' that do not comprise of any major improvements w.r.t state of the art. Score of 2 indicates 'medium novelty idea' that comprises of Ideas that caters to a new functionality. Score of 3 indicates 'high novelty idea' that uses a new principle to perform the primary functions.

Net effectiveness score is computed by addition of average ease of charging score and perceived energy efficiency. With net effectiveness score of "40.5", novelty score of "14" for the ideas using the template and with net effectiveness score of "41.5", novelty score of "13" for the ideas without using the template our analysis indicates 'no significant difference' in terms of quality of the ideas generated with the tool and without the tool. However our evaluation is limited by knowledge about the potential of these ideas in terms of the criteria chosen and hence inherently subjective.

6 Summary and Conclusions

To summarise, the designers using the tool were able to generate ideas that had the potential for addressing a larger range of issues within given problem and that had the potential to cover broader dimensions of sustainability. Designers using the tool felt InDeaTe provided a common framework for approaching the problem and driving the design conversation forward. However more studies are required for validating the tool in a comprehensive manner. As research advance in the field of smart manufacturing, multi-criteria methods can be used such as novelty and variety of ideas produced for comprehensive evaluation of the outcome of the design experiments i.e. requirements and solutions for smart manufacturing in this case.

Ongoing work on development of the tool includes incorporation of feedbacks obtained from the design exercises, such as resolving usability issues, enhancing the databases and overcoming the limitations of study such as few problems, subjectivity of effectiveness metrics, and influence of domain knowledge.

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Appendix

See Tables 1 and 2.

Table 1 Evaluation of ideas generated using the InDeaTe template with the tool

Ideas on easy charging of sensors using the tool (less score is better principle)	Wired connection to sensor location	Wireless charging for battery	Harvesting energy from ambient light	Harvesting energy from vibration/sound	Harvesting energy from spindle rotation	Harvesting energy from machine movement	Net score
Time taken for charging	2	3	5	5	3	4	22
Simplicity	4	2	4	4	3	4	21
Energy loss	5	4	2	1	5	2	19
Net effectiveness	8	6.5	6.5	5.5	8	6	**40.5**
Novelty	3	2	2	2	3	2	**14**

Table 2 Evaluation of ideas generated without using the InDeaTe tool

Ideas on easy charging of sensors without using the tool (less score is better principle)	Using power from electrical supplies	Using generator coils around rotating elements	Using noise to generate energy	Using photovoltaic coatings on bearing surfaces	Converting thermal energy produced from heat dissipation	Using light harvesting nano-structures	Net score
Time taken for charging	2	3	5	5	4	4	23
Simplicity	4	3	4	4	4	3	22
Energy efficiency rank	5	5	1	2	4	2	19
Net effectiveness	8	8	5.5	6.5	8	5.5	**41.5**
Novelty	3	2	2	2	2	2	**13**

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