Application of InDeaTe Design Tool for Designing Sustainable Manufacturing Systems—Case Study of a Micro-hydel Turbine

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Abstract The InDeaTe design tool was developed to help designers and engineers to innovate by following a methodical process. This paper discusses the application of InDeaTe for designing a manufacturing system for a grassroots innovator who makes and installs small hydel power turbines in southern India. The aim of the design exercise was to help scale up the current manufacturing setup to cater to the high demand, while ensuring its sustainability. Two design teams were involved in solving the problem—one using the tool and the other without. Analysis of the final design outcomes showed that the team using the InDeaTe tool generated a more comprehensive design than the team not using the tool. This study indicates that InDeaTe tool can help in developing more inclusive designs for manufacturing systems. Future work on InDeaTe includes improving its usability and expanding its database.

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1 Introduction

About 237 million in India still do not have access to electricity as the grid still does not reach its remote areas [1]. Renewable sources of energy such as micro-hydel, solar, and wind depend on the location and geography, hence play an essential role to provide decentralized accessibility to energy. The estimated potential for micro-hydro projects in India is about 20,000 MW [2]. A hydro power turbine converts the energy from falling or flowing water into rotational mechanical energy. The selection of the best turbine for any particular hydro site depends upon the site characteristics, like available head and flow, and on the desired outputs like running speed of the generator and power load [3]. In most cases, a small hydro power plant is 'run-of-river'; i.e. a small barrage, usually just a weir, and generally with little or no storage of water. The civil works are merely for regulating the level of the water at the intake to the turbine. Therefore, run-of-river installations do not have adverse effects on the local environment like large hydro power plants [3]. While there is still no internationally agreed definition, anything between 10 and 200 kW is called a micro-hydro power plant, whereas anything less than 10 kW is called a pico-hydro power plant [3, 4]. In this study, we refer to anything less than 200 kW as micro-hydro.

The remote regions of Karnataka are power-starved as they cannot be connected to grid; nevertheless, the beautiful landscapes are laden with perennial natural water streams. To deal with the problem of electricity access and uncertain power supply, micro and pico-hydel power turbines are being used as alternative sources of energy. One grassroots innovator has been making and installing customized micro-hydel power systems of 1–10 kVA capacity through trial and error. There is tremendous potential for this product in hilly areas of the country, especially in the south, far north and north-east. In order to meet the anticipated demand, the subjects in this study were asked to design a sustainable manufacturing system to scale up the production of such turbines for the grassroots innovator. The resultant designs were compared to assess the improvement for sustainable manufacturing considerations, with and without the use of the InDeaTe Tool.

2 Design Exercise

2.1 Exercise Summary

The design exercise was undertaken in June 2015 at the Centre for Product Design and Manufacturing (CPDM), Indian Institute of Science (IISc), Bengaluru. The design problem was introduced by a representative from National Innovation Foundation (NIF), Ahmedabad. The exercise was conducted in two sessions with a separate team in each one using the tool and the other without. The design outcomes were presented and feedback was taken from NIF. The design outcomes were primarily analysed for improvement in sustainability of the system.

2.2 Exercise Duration

The exercise was approximately for 16 h, spread over two consecutive days:

Day 1—Introduction to Problem and Task Clarification;

Day 2—Conceptual Design and Embodiment Design.

2.3 Design Teams

Composition of the two teams was as follows:

Team 1 using the tool comprised two senior PhD students and one Undergraduate (UG) student in engineering.

One senior PhD Student, from IISc, was working on Design for sustainability, with background in Mechanical Engineering and Product Design.

The other senior PhD Student, from UC Berkeley, was working on Hydrogen fuel cells, with background in Mechanical Engineering.

The UG student was pursing B.Tech in Production Engineering from IIT Roorkee, India.

Team 2 without the tool comprised three junior PhD students and one Undergraduate student.

One junior PhD Student, from IISc, was working in the area of Network-enabled Manufacturing, with background in Mechanical and Biomedical Engineering.

One junior PhD Student, from IIM Ahmedabad, was working in the area of Water-Energy nexus for sustainability, with background in Environmental Engineering.

The other junior PhD Student, from WSU Pullman, was working in the area of Life Cycle Assessment (LCA), with background in Mechanical and Civil Engineering.

The UG student was pursing B.Tech in Mechanical Engineering from IIT Ropar, India.

3 InDeaTe Tool

There are various kinds of design support that focus on sustainability; however, most of these are for assessment and evaluation, such as the Swiss Ecoscarcity methods (Ecopoints) [5]. Certain tools such as DFE Workbench [6] are well-integrated with Solidworks CAD tools, and are able to support designers with respect to specific aspects of a design, environmental aspects in this case. There are other design methods that support only a specific phase of the Life Cycle e.g. the Use-phase [7].

Interaction of methods and tools at the various steps in the process of design has been noted in literature, and the need for interaction between design methods and computer-aided tools to support decision-making has been stressed [8]. Lopez-Mesa [9] enumerated potent findings about the knowledge and use of design methods in practice; she highlighted that very few methods are widely and systematically used, while most people are not aware of the availability of other methods, or believe that a large amount of time is required to use these methods. However, she notes that application of methods supports an array of tasks during the design process and leads to consideration of a large number of ideas. Lopez-Mesa further stresses that a method contributes better to the design when it is within a computer based system [9]. Thus, there is need for computer-based support that covers all three pillars of sustainability—environment, society and economy—across the entire life cycle of the object of design, and addresses the need for improving sustainability of existing systems, with the systematic integration, to practice, of methods and tools.

The InDeaTe Tool [10] 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 to support designers through a computer interface. The template is developed from the ACLODS framework [11] as the basis, which presents a new paradigm of design in terms of the dimensions of Activities, Criteria, Lifecycle (LC) phase, Outcomes, Design Stage and Structure. The tool introduces the user explicitly to some of these dimensions, viz. Activities, LC 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 process. Four stages of design have been prescribed Task Clarification, Conceptual Design, Embodiment Design and Detail Design [12]. Every design has up to five Life cycle phases: Material extraction, Production, Distribution, Use and After Use. The Template encourages designing for the entire LC of the product, with the aim of making it more sustainable. At any point in the design process, designers perform one of these four activities Generate, Evaluate, Modify, and Select; abbreviated as GEMS.

The database consists of sustainability definitions, sustainability indicators and design methods, tools and principles. The definitions are meant to help clarify the design task at hand with respect to the sustainability perspective adopted, while the corresponding indicators prompt the relevant sustainability considerations in the design. The methods are intended to aid the designer in the design process to achieve these sustainability considerations. The tool is a platform where the template is introduced and the details of the design exercise, such as problem brief and details of participants, etc. are collected into a document for future reference. Before starting the design exercise, the user selects the type of design; the InDeaTe tool currently supports design of products, manufacturing systems and service systems.

4 Solution Without Tool

The team without the tool first analysed the current situation, taking into consideration the market conditions, policies and socio-economic aspects. They identified the criteria and categorised these as per the triple bottom line. Requirements and solutions were identified for concepts as per the life cycle phases. Finally, recommendations were made for design, manufacturing techniques and supply chain activities for the turbines. The following section presents the process undertaken to arrive at the final outcome.

4.1 Current Situation

As per the problem brief given by NIF, the existing market demand of micro-hydel power plants in the state of Karnataka and regions in the North-East was estimated to be around 2000, with an overall market potential of 8000 micro-hydel turbines in India. The grassroots innovator is currently able to supply only two customized turbines per month, so the annual supply runs at 24. There are very few grassroots suppliers that can supply cost-effective and sustainable turbines, so the demand will remain more than its supply. Additionally, BSNL, a public sector telecom company, has expressed interest in setting up micro-hydel power plants to power 100 cell towers in the remote regions of Karnataka.

The team considered the market condition along with other parameters such as the current policies and technology available in the country. In the current scene, there is no competition for the innovator in micro-hydel systems; however, there remains competition in terms of cost, efficiency, durability and accessibility from other sources of energy such as diesel, solar and wind. Solar and wind cannot compete with diesel in terms of easy accessibility. However, with subsidies and national and state push on renewables, they will become competitive in terms of costs. The innovator has been foreseen to dominate the market if he scales up his operations. However, with market expansion, problems of durability and service would occur after installation. Unlike diesel generators, skilled personnel are required for operation and maintenance of micro-hydel power system to be sustainable over longer period of time. Additionally, there remain socio-cultural challenges in terms of acceptability, economic challenges in terms of affordability, and technical challenges in terms of efficiency and use for such systems with increasing number of electrical appliances. Both end users and vendors need to be educated and be aware both about the product and its operation and maintenance.

4.2 Criteria

The principle selected by the team without tool to work on the problem was triple bottom line, as it factored for sustainability and looked into its three main pillars: (1) Environment, (2) Economics and (3) Society. The environment parameters considered are resource use, pollution in the form of emissions and effluents, and their impact on human as well as natural ecosystems. The economic parameters considered are cost and efficiency of the technology, market conditions for diffusion of the technology and development of local economy. The social parameters considered are social responsibility of manufacturers, vendors and users.

4.3 Ideas for Improvement

The team went through several design stages in order to arrive at an understanding of the problem and getting a structure to solve it. They considered the life cycle phases of the turbines: material extraction, production, distribution, use and after-use. The team followed the life cycle phases as a couple of the students were familiar with the concept. The group then deliberated on each of the phases and the elements required for the given problem. The material extraction stage involved looking into issues such as local sourcing of materials for manufacturing the power systems. The aim was to redesign with less, but quality material, and use of recyclable and reused materials and parts. The production stage had to be revamped, as the main objective was to scale up the process. The team had to redesign the process to make it easier for the manufacturer, and also easier for assembly/disassembly before and after use. The process of scaling up required more manufacturing locations, and efficient and cheaper transportation and distribution systems. There had been problems faced in the operation and maintenance of the product, which the innovator was able to deal with as the clientele was small and local. With scaling up, the innovator would need to look into long term operations, and safety during use. Additionally, the group had to minimize downtime and during disasters. In the after use stage, aspects such as design for disassembly, incentivising recycling, and programmes to encourage secondary market for robust parts having longer lifecycles were considered.

Elaboration of major ideas: Three of the several solutions discussed in each of the life cycle stages, over 8 h, were narrowed down by the group to improve the process design. These were the following.

1. **Decentralize Manufacturing**: The group recommended a hub and spoke model which encourages creation of manufacturing hubs, one each in Karnataka and North-East. This should be followed by building smaller hubs to facilitate transportation and distribution of the power systems in smaller towns, with final assembly taking place on-site. This should reduce packaging and generate more jobs at the smaller hubs.
2. **Standardize Designs/Components**: The design of the power systems in each of the 1, 2, 5 and 10 kVA capacities vary considerably. This required customized manufacturing and availability of raw material. In order to scale up, there is a need to standardize a proven design for the generator set in each capacity. This in turn will increase manufacturing efficiency (making a lot of the same is easy), minimize number of spare parts to deal with, and ease the repair process during operation and maintenance.
3. **Improve Cup Design**: The cups of the pelton wheel provided in the pictures above vary in size. The design of cups like the generator set needs to be standardized in order to improve efficiency and make it easier to manufacture at less energy and costs.

5 Solution with Tool

The team using the template identified the scope, the issues to focus on, and the list of requirements for clarifying the task using the methods given in the database. Production and use were identified to be the most critical life cycle phases; hence, relevant indicators were chosen to improve these phases. The weighted objectives method was used to prioritise the requirements. The team generated several concepts, of which one was selected by consensus. The 6R principle was followed throughout.

5.1 Task Clarification

The main objective of the solution was to create an affordable manufacturing system that does not compromise on the performance of the turbines. The size, materials, layout and energy generation technology were all recommended to be changed according to the design. The principle, indicators, life cycle phase, components to be changed, and the requirements are listed below.

Principle: The main principle chosen to improve the process design was 6R which is an acronym for reduce, reuse, recycle, refurbish, redesign, and repair.

Indicators: Indicators were chosen based on the selected principle. These include: resource use, environmental indicators (climate change, GHG), production cost, employment, flow rate, raw materials, energy input, energy efficiency, energy consumption, raw materials, quality, and less materials.

LC Phase: As mentioned earlier, in order to improve the process at minimum costs, production and use (operation) phases of the lifecycle were chosen as they both ranked high in priority areas that needed attention for sustainability.

Components: The components chosen to work on the design were the supporting Frame, and the main focus was on Pelton wheel due to lack of time.

List of requirements to improve the Pelton wheel are as follows:

1. Pelton Wheel manufacturing process standardization;
2. Safety (during installation and use);
3. Scales of MHET for different requirement profiles;
4. Alternative use of drive.

Method Used: The methods used to narrow down the aforementioned choices were weighted objective method and expert opinion.

5.2 Conceptual Design

Ideas were generated, evaluated and recommended for the following requirements.

Standardization:

- Scales of MHET for different profile requirements: different head requirements for varying geographic locations
- Provision to add more weights to the flywheel
- Provision for variation in the supporting frame
- Standardizing for supporting frame and wheel
- Increasing diameter of flywheel
- Variable diameter wheel.

Safety:

- Installation
- Use/operation.

Alternative uses of drive and generated electricity (add on):

- Flour mill
- Agriculture purpose: sowing/irrigation
- Ideas from Power Take-Off of Tractor.

Inputs from the innovator:

For standardization, the 1 and 2 kVA units are very similar and they have larger volume requests than other units. The 1 kVA turbine has 18 cups on a flywheel of diameter 1.5 feet and weight 20–30 kg. The 2 kVA turbine has 26 cups on a flywheel of diameter 2 feet and weight 40 kg. The main challenge faced by the

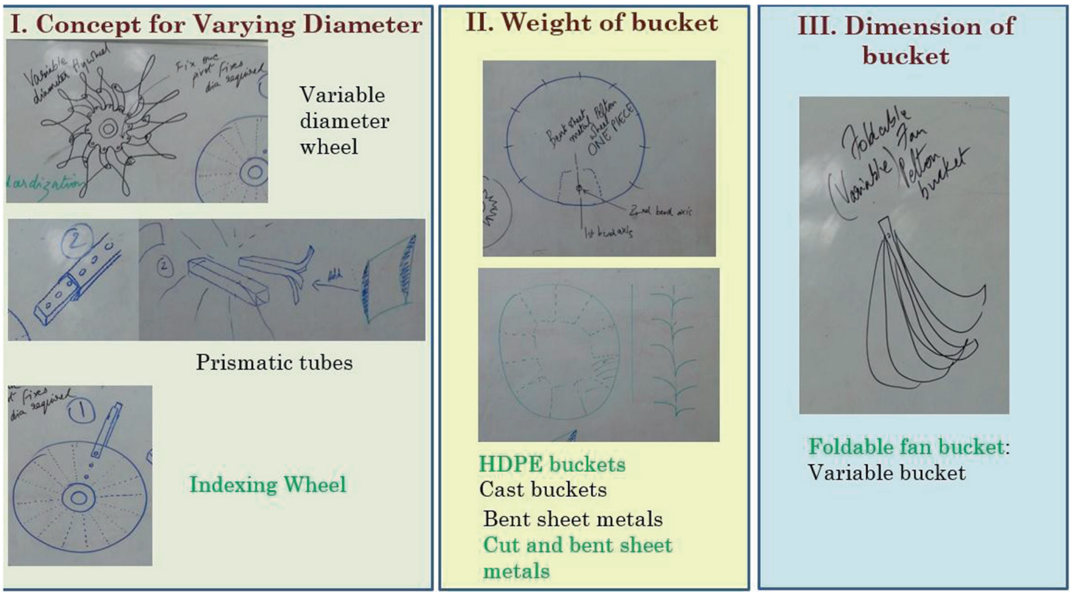

Fig. 1 Concepts generated by the team using InDeaTe tool

innovator was to standardize for Flywheel Weight, Bucket Variation, Pelton wheel, and Alternator. Concepts for the Pelton wheel were generated, see Fig. 1. The design of the diameter and type of wheel, the weight of the bucket and dimension of bucket were discussed as an example to improve the design of the wheel.

5.3 Embodiment Design

Due to lack of time only two of the generated concepts in varying diameter of the wheel were compared. They both have foldable fan buckets mounted on the indexing wheel; one has buckets made of HDPE while the other has buckets made of Sheet metal. The first concept, consisting of Indexing Wheel, Foldable Fan Bucket and Bent Sheet Metal buckets was suggested as the solution based on consensus. If more time were available, this would have led to conducting comprehensive analyses in each of the selected phases and generated concepts. Provision of time frame during this stage alongside the methods used can be helpful to the users of the database.

6 Analysis of Design Processes

In this study, the controlled variables include the participants' educational background to a certain extent, the given problem, expert intervention, template of the tool and the associated database, whereas the uncontrolled variables consist of the participants' prior experiences, individual and group dynamics. Although the team using the tool did not explicitly refer to any particular definition of sustainability, they chose all the indicators related to production and use phase. The team without tool did not know how and where to begin and lacked structure in their approach. They felt that having specific goals would have helped to focus and avoid the initial day confusion which resulted in a slow start. In the absence of structure, the group ideas argued on solutions without identifying requirements. They, however, followed the triple bottom line principle [13] and life cycle analysis as method, to generate ideas as per the five phases of the life cycle. Their familiarity with these concepts could be attributed to their educational background. On the other hand, the team using the tool focused on certain specific requirements after prioritisation, but they could not evaluate the solutions generated due to lack of time.

The team without the tool did not use formalised methods to identify the task and evaluate the requirements as they had no structure resulting in generalized suggestion over all the phases. The team using the tool used the weighted objective method for selecting the most promising requirements. They generated ideas by brainstorming and selected the most promising solution by consensus. Owing to insufficient data and time constraints, they were not able to perform any detailed calculations. Life cycle cost analysis (LCC), vulnerability assessment (VA) and Social Impact Assessment (SIA) were recommended if more time was provided.

7 Conclusions

This study suggests the importance of method and structure in solving a design problem. InDeaTe tool was able to provide the group of designers and engineers to comprehensively solve a problem at hand by prioritizing based on time, cost and principles of sustainability. The solution provided was observed to be deliberated on in a more systematic manner. The team without the tool struggled to get a structure resulting in loss on time. They ended up discussing solutions, without discussing the purpose of the solution. The experiment showed that a skilled person without design background will find the tool difficult to follow. The tool is primarily meant for designers, and there is a need to make making it more user-friendly and to include other set of skilled users (like engineers). Providing tutorials and training modules will give it a broader appeal, thereby making it available to users without a design background. There is a huge scope for improvement in the database, which should be made more comprehensive, so that a wider range of possible scenarios, time-frame and difficulty level could be addressed during the design process. Future work will involve applying the tool on a wide variety of manufacturing system design problems, in addition to improving the database and its usability aspects.

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