SUPPORTING ENVIRONMENTALLY-BENIGN DESIGN - ELUCIDATING ENVIRONMENTAL IMPACT PROPAGATION IN CONCEPTUAL DESIGN PHASE BY SAPPHIRE MODEL OF CAUSALITY

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Abstract

Conceptual Design Phase is the most critical for design decisions and their impact on the Environment. It is also a phase of many 'unknowns' making it flexible and allowing exploration of many solutions. Thus, it is a challenge to determine the most Environmentally-benign Solution or Concept to be translated in to a 'good' product.

The SAPPhIRE Model captures the various levels of abstractions present in Conceptual Design by Outcomes and defines a Solution-variant as a set of verifiable and quantifiable Outcomes. The Causality explains the propagation of Environmental Impact across Outcomes at varying levels of abstraction, suggesting that the Environmental Impact of an Outcome at a certain level can be represented as a collation of Environmental Impact information of all the Outcomes at each of its subsequent lower levels of abstraction. Thus a ball-park impact value can be associated with the higher-levels of abstraction, thereby supporting design decisions taken earlier on in Conceptual Design directing towards Environmentally-benign Design.

Keywords: Conceptual design, Decision making, Early design phases, Environmentally-benign Design, SAPPhIRE Model of Causality

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1. INTRODUCTION

Our world today is home to over seven billion people, constantly striving to meet its ever-increasing needs and unwarrantedly exploiting the environment to achieve it. Design aims at “changing existing situations into preferred ones” (Simon,1981). As Gero (1990) succinctly puts it, design exists because the world around us does not suit us and the goal of the designer is to change the world through the creation of artefacts, or products.

Product design, though amounting for only 5% of the entire cost of a product, commits about 70% of the entire project cost. It has the ‘power of both satisfying a need and providing value’ (Williams, 2007). In product development, product design determines the life cycle of the product and in turn, can determine the environmental impact of that product and so, products should be developed with reduced environmental impacts so as to restrict the environmental risk to future generations (Zust, 1992)

A number of environmentally conscious design methodologies , such as DfE, Eco-design, Green design, etc., already exist; the general goal of these approaches is to reduce the negative environmental impact of a product throughout its life cycle (Coulter, et al., 1995). Environmentally-benign Design is a strategy that propagates the same ideology and maybe defined as, designing with less or no harmful effect on the environment.

Design, and design changes, can completely change a product's environmental footprint (Kotelnikov ,2004) thus the intent of Environmentally-benign Design is to support designers make those design changes that reduces the environmental footprint of the product by aiding design decision.

Essentially, the engineering design process in its simplest form is a ‘general problem solving process’ (Hurst, 1999) and its goal is to synthesise alternative systems that perform the desired functions, meet the performance standards, and satisfy the constraints (Wood & Greer, 2001). However it is in the Conceptual Phase of design where the designer ‘takes the statement of the problem and generates broad solutions to it in the form of schemes’ (French,1999).

The Engineering Design Process, as illustrated by Pahl & Beitz, states that Conceptual design is the part of the design process where the basic solution path is laid down through the elaboration of a solution principle. Conceptual design specifies the principle solution or concept. Chakrabarti & Johnson (1999) point out that a principal task at the conceptual design phase is to consider the ‘widest possible variants of solution principles for subsequent embodiment into viable concept variants’.

Literature states that conceptual stage of design is critical as it determines the lifecycle of the product, affects all downstream processes and is ideal “time to solicit green ideas” (Srinivasan, 2009) .It further stresses that decisions during this stage have a great effect on the environment impact of the product (Kotelnikov, 2004) and goes on to add that the cost and environmental effects associated with a product are largely determined during conceptual design.

It is also, at this very phase of design that majority of product characteristics are determined and hence the time for designers to assess and choose the best concept to be embodied into a product. (Sarkar et al. 2009) As decisions made during conceptual design that raise costs and increase environmental impact that cannot easily be undone and rectified during detail design, it is imperative that the right decisions are taken. Thus Environmentally-benign Design at the conceptual phase of design shows great promise as it aims to support design decisions at early stage of product development, much prior to embodiment, saving time, effort and money.

The Objectives of this paper are as follows :

1. To discuss current eco-design methodology for integrating Sustainability into Product design at conceptual design stage - FIM. A quick study to understand evolution of a design illustrates that this methodology does not capture the entirety of the information, at times ambiguous or

unknown, prevailing at various levels of abstraction as is characteristic of conceptual phase of design. This is presented in Literature Review. Thus, we hypothesise that there is a requirement for a 'richer' description of design that captures abstraction

2. To elucidate with example that the SAPPhIRE Model of Causality provides one such possible rich description through its seven constructs (State Change, Action, Part, Phenomenon, Organ, Effect) which are Outcomes of any design at varying levels of abstraction. These Outcomes available densely at certain mid- and lower-levels of abstraction consistently across solution-variants of a problem, are verifiable and quantifiable . Thus, we hypothesise that this model defines Solution-variant as a 'Set' of verifiable and quantifiable Outcomes which can be used to evaluate environmentally-benign most solution-variant. This is addressed with Literature Review and Descriptive Study.

3. We argue that the SAPPhIRE model of causality can explain the propagation of environmental impact across Outcomes from lower to higher levels of abstraction and can be used to estimate the Environmental Impact for different level Outcomes. This is graphically represented where Environmental Impact value is presented as a 'set' of values, increasing with each higher-level Outcome becoming a 'super set' and further illustrated with an example.

The intent of this research is to support environmentally-benign Design by estimating the Environmental impact of a design at various levels of abstraction to aid design decision during Conceptual Phase.

2. DESIGN DESCRIPTIONS AND IMPACT ASSOCIATION

In his seminal work 'Design Prototypes', Gero (1990) asserts that the result of the activity of designing is a design description and it (designing) is a process that aims to create the structure of artefacts that meet a set of requirements stated as functions. He further adds that it (design description) is generally represented graphically, numerically or textually; its purpose is to transfer sufficient information about the designed artefact.

2.1 Discussion on current eco-design methodology (FIM) : Literature Review

Researchers at Purdue University, CDI Lab proposed a novel eco-design methodology called the 'Function Impact Matrix' (FIM) for integrating sustainability into Product design at Conceptual Design Stage (Devanathan et al., 2010), that aims to balance qualitative and quantitative data while integrating environmental sustainability considerations into early design process. Authors stress the importance of relationships or mappings between Functions, Behaviours and Structures of a design and its environmental impact. A main aspect of the FIM is to identify product functions are important from an environmental perspective and functions to be re-examined in order to achieve a better eco-design

2.1.1. FIM : The Methodology

As per the FIM Methodology, all new designs are considered to be a combination of existing concepts. Bearing this in mind the following activities are performed;

- Product tear-down and benchmarking is done during which designers identify Function-Behavior-Structure of the benchmarked product.
- LCA results of similar products are analysed to relate the engineering characteristics to environmental performance.
- To facilitate design concept development, a Function Decomposition is usually conducted. A correlation that connects Functional information to environmental impact data through the Structure of an existing product is identified with respect to which environmental impact estimates are assigned to each function.
- Finally, the life cycle Environmental Impacts are then allocated to all the sub-functions and in turn, these sub-functions are fused to generate concepts.

2.1.2. FIM : Strengths of the Methodology

The main goal of the FIM is to identify the importance level of each function and determine the functions, which should be re-examined to obtain a better design from an Environmental perspective. This methodology might prove to be useful for developing 'modifications' and bringing about incremental 'improvements' in existing products in short duration.

As found by the authors, from a designer's perspective, the Function-Impact method provides an easy-to-use visual interface for LCA data (Bernstein et al.,2010). Designers thereby have access to meaningful visual representations of real LCA data, probably improving the interpretation, in turn, increasing the integration of this information.

2.1.3. FIM : Shortcomings of the Methodology

Authors, Devanathan et al. (2010), themselves mention that Function-Impact may reveal functions which contribute disproportionally to the overall environmental impacts and that the development of F-I correlations is very likely to be case specific. They further note, that if a new concept lacks functional similarities with other products, the Function-Impact approach cannot be used directly.

Finally, the authors argue that 'concept design is generally function focused, and almost all new designs are actually novel combinations of existing functions/concepts of existing products of similar or different types' (Bernstein et al.,2010). We find accepting this premise difficult and question it with a quick study on evolution of a design.

2.2 Understanding Evolution of a Design : A Literature Study on The Time-piece

A Time-piece is an instrument to measure time. The concept of a 'time piece' has been part of the human civilisation since the era of the sundial, and has developed from Water Clock or clepsydras to Pendulum Clock to Crystal Quartz Clock to Atomic Clock (Rioukhina, 2008).

2.2.1 Observation : It is inadequate to map Function through Structure

Though the intent of the design remains the same, the means to achieve it i.e., the Function - to tell time - evolves or grows with many new, unknown functions being added.
And thus,

- not all Function or Structure maybe known or explored — This gives rise to the scope of innovation.
- there is also a possibility of 'creating' new Structure to fulfil a known Function — This is how Inventions arise

Thus, to consider the 'set' of knowledge or information corresponding to Function or Structure to be complete, novel combinations of which will give rise to new designs, is highly limiting.

2.2.2 Observation : 'Working principle' is key to product design evolution

With development of technology and innovation, evolution of the 'working principle,' i.e. the physical phenomenon and effect necessary for the design to function, is observed leading to generation of new Structures to satisfy it.

For e.g. : the Principle of Oscillation is used in all three latter designs but via different Structures, such as, mechanical spring-coil mechanism in a Pendulum Clock, vibration of quartz crystal oscillator in an electric field in a Crystal Quartz Clock and oscillations of atoms of caesium-133 in an Atomic Clock.Therefore,

- a Function maybe satisfied by various Working Principles, which in turn can be satisfied with multiple Structures
- the Working Principle being at a higher level of abstraction, maybe considered fairly independent of the Function or Structure.

Therefore, by varying the Working Principle features, i.e., Physical effect and Material/Geometric Characteristics, Principle Solution variants can be explored and created. This is already argued by, among others, Pahl & Beitz (1988).

2.3 Design Description : Summary & Conclusions

2.3.1 Summary

Conceptual Design phase is characterised by ambiguity and inconsistency in the information available. It is highly unlikely that all Functions of a concept are known or all Structures fully developed at this stage. However, the 'working principle' behind a concept, though highly abstract, is found to be far less ambiguous as it is grounded in physical laws and effects. It explains 'the How' behind the design.

One of the primary motivations in conceptual design is to explore, innovate and develop 'new and unknown' solutions to existing problems, and sometimes explore and address 'new and unknown' problems. But these 'unknowns' are not adequately captured under the pretext that all designs are composed of existing functions, making the application of this methodology highly specific and limited.

2.3.2 Conclusions

A description of design is required that is generic in application, addresses the abstraction inherent in conceptual design and captures 'How a design works', even if highly abstract, as it can overcome the ambiguity despite lack of precision of information.

Thus, we hypothesise that ***a 'rich' description for design at conceptual phase, capturing the relationships between the various levels of abstraction and working principles behind the design, is necessary for comprehensive Environmental Impact association.***

3. SAPPHIRE DESCRIPTION OF CONCEPTUAL DESIGN

Cross (2000) stated that design problems (can) have many different levels of generality or detail and that in the early stages of design, the designer moves freely between different levels of detail. According to the Integrated Model of Designing proposed by Srinivasan & Chakrabarti (2010), during designing, designs evolve through multiple levels of abstraction; each level providing a particular description of the design where descriptions at higher levels of abstraction provide greater flexibility in the interpretation of the design by committing less to its details.
They go on to stress that a conceptual solution can be described as a causal network of physical effects.

3.1 SAPPhIRE Model of Causality : Literature Review

The SAPPhIRE model was developed for capturing the functionality of systems that use physical phenomena for attaining their goals (Chakrabarti et al., 2005).

It consists of the following constructs (Srinivasan & Chakrabarti, 2009): Parts, Physical Phenomenon, State (change), Physical Effect, Organ, Input, Action. The relationships between these constructs are as follows: parts (P) of a system and its surroundings create organs (R), which are the structural requirements for a physical effect (E). A physical effect is activated by various inputs (I) on the organs and creates a physical phenomenon (Ph), and changes the state (S) of the system. The changes of state are interpreted as actions (A), as new inputs, or as changes that create or activate parts
The SAPPhIRE model makes explicit use of effects in describing the causality of systems, thereby describing the role of effects in explaining the outcomes of designing. It also accommodates three major representations of function—action, state change and input, thereby, providing a rich description of function. During designing, a single-to-many mapping from a higher to a lower level of abstraction is expected, resulting in development of a variety of alternative concepts.

SAPPhIRE is a model of Outcomes, developed to explain the causality of natural and engineered systems (Srinivasan & Chakrabarti, 2010). An Outcome is defined as a property of a design at an abstraction level and therefore is a type of product knowledge. Outcomes exist at different levels of abstraction. As designing progresses, the abstractions reduce and the Outcomes become concrete. In other words, the uncertainty of Outcome decreases.

Thus, the SAPPhIRE model is the 'rich' description that is required for a design at Conceptual Design Phase as it can capture the relationships between the various levels of abstraction in which information is present and the working principle behind the design.

3.2 SAPPhIRE Model - Appropriateness and 'richness' in description at the Conceptual Design Phase : A Descriptive Study

To further explore the appropriateness and 'richness' of description of a design at Conceptual Phase, with respect to SAPPhIRE model, a descriptive study is undertaken. A Design Experiment (from archives) is analysed to understand the evolution of Solution-variants and how information arises as a design develops.

A design brief is given to designers, which elaborates the problem and clarifies the essential task to 'design a portfolio of furniture which will help to sit, write and eat while considering the issues mentioned above. The brief also descries the Lifecycle Stages of a Product. The designers then clarify the requirements and develop conceptual solutions to the problem that are recorded and analysed using video protocol analyses. The following observations are made by analysing these protocols.

3.2.1 Observations :

Conceptual Design phase is characterised by ambiguity and inconsistency in the information available.

A designer begins with available information as present in the Design brief. (Refer to Table 1)
The designer accepts/discards various portions of the brief and decides to address his own set of Problems posed in the Design Brief. This is consistent with the Requirement identification step as per Pahl & Beitz (1988).
The designer accepts/discards various portions of the brief and generates his own set of Requirements & Inputs from the given Problem statement. This is consistent with the Abstraction step of conceptual design as per Pahl & Beitz (1988).

Table 1. DESIGN PROBLEM & REQUIREMENT ANALYSIS

Issues & Problem	Need to transfer often	Heavy or Bulky furniture	Occupies lot of space	Takes time to pack	Not Economical to buy & sell	Gets damaged in transit	Set-up time & effort of user minimal	Lifecycle Consideration
Designer 1			y	y	y		y	y
Designer 3	y	y	y					
Designer 5	y		y	y	y		y	

From his own set of Requirements, the designer generates solutions which appear at higher levels of abstraction such as Action or State change. This is consistent with the Establish Function Structure step of conceptual design as per Pahl & Beitz (1988).

At this point, it is interesting to note that solutions are also generated at lower levels, particularly Part-level. Here one must consider the issue that Designers exhibit fixation through pre-structuring requirement or pre-determining solution.
Though not explicitly, the sketches and words of the designers, reveal that they explore certain Phenomena and oRgans, that fulfil the desired Effect, necessary to achieve the desired solution-variant having the previously generated or newly generated Parts. This is consistent with the steps 3,4,5 of conceptual design as per Pahl & Beitz (1988).

Concepts or Solution-variants are further developed upon considering one or more of the previously deduced solution at higher level of abstraction & conceptualisation is completed with characteristics that correspond to constructs at lower levels of abstraction. Please refer to Table 1 and 2 to explain or exemplify.

Table 2 CONCEPT GENERATION - TREE OF ALTERNATIVES

Out-comes	Sol-Variant 1.1 - BED WITH STORAGE		Sol-Variant 3.2 - MULTI-UTILITY FURNITURE MODULE		Sol-Variant 5.1 - FOLDING BED			Sol-Variant 5.2 - COLLAPSING BED		
A		***Modular***			***Flexibility***					
	Foldable		***Foldable***		***Foldable***			***Expandable***		
S	1) *from OPEN usable state to FOLDED wall mounted unusable state* 2) from UNASSEMBLED to ASSEMBLED		Change in no. of basic units and joints, dimension, form		from OPEN Horizontal usable state to FOLDED unusable state			from CLOSED to EXPANDED, X-lattice Frame		
PH	Compression	Torque	Shear	Compression	Tension	Compression	Torque	Tension	Compression	Torque
E	$\sigma = \frac{F}{A}$	τ = r F sinθ	$\tau = \frac{F}{A}$	$\sigma = \frac{F}{A}$	$\sigma = \frac{F}{A}$		τ = r F sinθ	$\sigma = \frac{F}{A}$		τ = r F sinθ
I	Light weight, strong material, Modular		Good form, Minimal (no. of) parts, Replaceable parts							
	Force (upward) applied to lift		Force to assemble		Force (upward) to collapse			Force (downward) to collapse		
oR	*(Fix to) Slots in perpendicular Modular unit members forming a Box structure on a Hinge :* Volume of body encompassed + light weight and high Compressive strength + degrees of freedom		*Unit components which allow joinery at the ends*; Area of body + Compressive and Tensile strength		*Hinges between members :* Area of body + high Compressive strength + degrees of freedom			*Scissor Hinge array of members :*Area of body + high Compressive and Tensile strength + degrees of freedom		
P					***SS hinges & stopper, Belt & Board***			***Net*** (material &/ geometry unspecified)		
	Plastic (material class, geometry unspecified)		***Wood/ Mdf/ Plastic***		(material & geometry unspecified)			***Wood/plastic Supports*** (material class known; geometry unspecified)		

KEY ____ INFORMATION AS PROVIDED BY DESIGNER ___ INFORMATION AS INTERPRETED BY

3.2.2 Summary of findings from the Descriptive Study :

Given the Outcome information made apparent by the designers, we find the following;
• That the SAPPhIRE analysis reveals the concept-generation activity evolves as a Tree of Alternatives, terminating at distinct solution-variants.
• Mapping occurs from higher to lower level Outcomes and 'gaps', predominantly at the mid-level of Outcomes, are present. This is already supported by literature.
• It is interesting to note the Outcome information available. Figure1 diagrammatically represents the number of different Outcomes at different levels of abstraction, that arises during conceptual design generation.
• Design progresses from higher level Action to lower level Part Outcomes, as denoted by the arrow from A to P. Contrary to assumption that information will streamline as it moves towards the lower level, a broad set of Outcomes are observed at the higher-level.
• It is at the mid-level of abstraction where abstract ideas manifest into concrete Outcomes of Phenomenon and Effect and a more confined set of Outcomes is observed.
• This further guides the characterisation of the Solution with the lower levels of organ and Part Outcomes, where again a broad set is observed.
• A number of Actions can be achieved by a particular Phenomenon whereas a single Action may be achieved by a set of Phenomena, same as or overlapping the previous set. Similarly, a number of Parts and oRgans in turn can achieve a Phenomenon or a set of Phenomena.
• Solution-variant is a 'Set' of mid- and lower-level Outcomes (Ph, E, oR and P), derived from a set of higher-level Outcomes for a set of Requirements selected from the overall Functional Requirements, by designers, from the design brief.

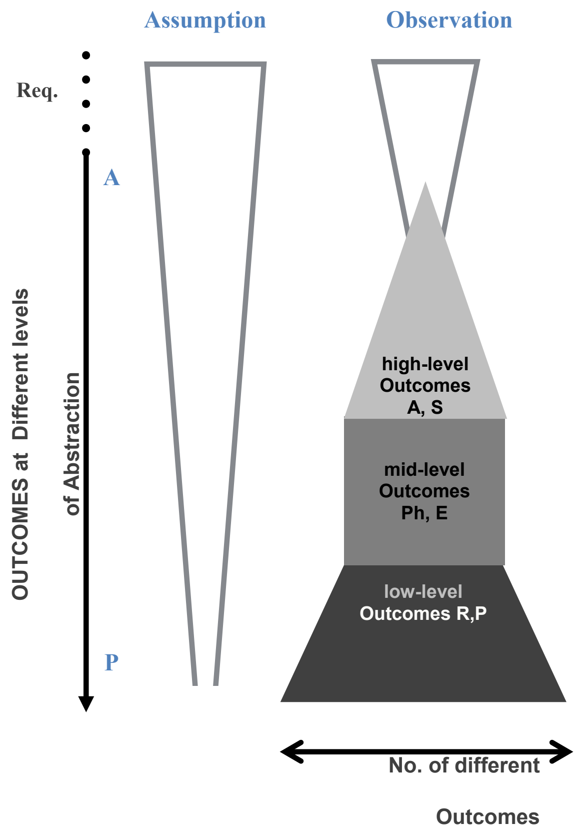

Figure 1: Diagrammatic representation of Outcome information available at Conceptual Design

3.2.3 Conclusions from the descriptive study :

• A Solution-variant, though exhibiting the higher-levels of abstraction (A & S) as attributes, can truly be substantiated by verifiable Phenomena and Effects, achieved by a set of quantifiable (within a range) Parts and oRgans.

3.3 Research Hypotheses : Validation and Inference

• From the Literature Review and Descriptive Study, our hypotheses are strengthened. First, it was found that Conceptual Design has information at various levels of abstractions which cannot adequately be captured by Function, Behaviour and Structure alone and hence, requires a richer description. The SAPPhIRE model offers a possible 'richer' and appropriate description of design at this Phase as it captures the relationships between the various levels of abstraction in which information is present.

- Further, the review and the study support supports our second hypothesis that the SAPPhIRE model defines Solution-variant as a ‘Set’ of verifiable and quantifiable Outcomes. It is found that a Solution-variant is a ‘Set’ of Ph,E,oR and P-level Outcomes, each of which is verifiable and quantifiable (within a range) and has the capability to overcome the ambiguity despite lack of precision of information, by mapping one level to another.

- Finally, the SAPPhIRE model uses effects and since essentially both ‘effect’ and ‘Impact’ have the same connotation, i.e., being the result, achieved by a ‘cause’. We infer that the model for causality can be borrowed for mapping the propagation of Environmental Impact across the levels of abstraction.Thus, we hypothesise **that *the SAPPhIRE model of causality explains the propagation of environmental impact across Outcomes from lower to higher levels of abstraction and can be used to estimate the environmental impact of Outcomes at different levels*.**

4. IMPACT PROPAGATION AND DESIGN DECISIONS

For successful generation of Environmentally-benign solution-variants, it is imperative at this stage of Conceptual Design, that Environmental Impact values of the Solution-variant’s Outcome-Set be available for evaluation.
The intent is to associate environmental impacts to the Outcomes : Ph, E, oR or Part, such that collating these would allow the designers to obtain an estimate on the Environmental Impact of the potential Solution-variant they are conceptualising thereby, indicate support for the above hypothesis.

4.1 Environmental Impact propagation and value association : A Descriptive Study

Through an example of an architectural design problem ‘Design for Building Lighting Solutions’, from an empirical study of a design session that involved experienced as well as novice designers, we elucidate the impact propagation. We deconstruct Conceptual designs created during the session using the SAPPhIRE model and illustrate its Outcomes via an Environmental Impact Propagation Tree (Figure 2), similar to the Tree of Alternatives.

Figure 2: Environmental Impact Propagation Tree

In the Environmental Impact Propagation Tree (Figure 2), the Outcomes are represented by nodes branching off to subsequent low-level Outcome nodes. The arc connecting two (or more) branches at a node represents an 'AND' condition, i.e., the subsequent nodes are both part of that node. For example, the Phenomena 'Absorption' and 'Dispersion' are part of the Phenomenon 'Refraction'.

4.1.1 Observations and Impact value association method

It is observed, as expected, that a number of solution-variants are developed by the designer where a certain degree of detail in terms of Material class or Form/shape is considered. However, a variant lacks details with respect to Process, Dimensions and Relations. This observation is consistent with literature (Kota & Chakrabarti, 2006). It is fairly easy to associate an environmental impact value or score to the Part-level, such as material class, using various tools such as Eco-Indicator-99.

For the given example, we find with reference to Eco-indicator 99 Manual, Appendix (2000), the scores as millipoints per kg of the following Part-level (P) Outcomes with material class detail :

P : Wood [6.6 - 39] ;
P : Glass [49 - 51] ;
P : PVC [240 - 280].

Thus, going by the hypothesis the propagation of impact values along the flow of causality, the Environmental Impact of the following Phenomenon-level (Ph) can be indicated as :

Ph : Refraction [6.6 - 280] ;
Ph : Dispersion [240 - 280] ;
Ph : Absorption [6.6 - 51] .

Since the State Change-level (S) : f*rom more light to adequate*, is fulfilled by one Ph : *Absorption*, it can be interpreted that this 'S' is the most Environmentally-benign Outcome for achieving the Action :

f*acilitate natural light into building* and so, solution-generation should pursue this line of impact propagation.

Though a crude representation, not considering the subtleties of the other in between levels of abstractions, still provides an approximate range of values within which the environmental impact of the Solution-variant operates. The Impact information presented as a ‘set’ of values, increasing with each higher-level, Outcome becomes a ‘super set’.

4.1.2 Conclusions of from the Descriptive Study

- Thus, it can be said with confidence that

• Environmental Impact of an Outcome at a certain level of abstraction can be represented as a collation of Environmental Impact of all the Outcomes at each of its subsequent lower levels
• The higher the level of the Outcome, richer is the information available as it encompasses a bigger set of possible ways of fulfilling the intent. Therefore, it could be concluded that support provided for Design decisions taken at higher-levels of abstraction, earlier on in Conceptual Design could be used to direct the Activities towards Environmentally-benign Solution-variants.

5. CONCLUSION AND FUTURE WORK

Conceptual Design Phase is the most critical in terms of design decisions and their implications on the environment. This project aims to aid designers determine the most environmentally-benign Solution-principle or Concept, that would eventually translate to a ‘good’ product.

Environmentally-benign Design can be supported at conceptual design phase by providing the designer a ball-park estimate of the Environmental Impact of Outcomes at varying levels of abstraction, a set of which constitute a Solution-variant. This should, in turn, aid design decisions at higher levels of abstraction during conceptualisation without committing to details.

Our future work will focus on improving the environmental impact estimation with uncertainty considerations so as to, strengthen design decision-making at Conceptual Phase of Design.