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Assessment of structuredness of problems in design

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Abstract

Design problems are wicked in nature. Wicked problems are difficult to understand, formulate and solve. The literature focuses mainly on the characteristics of wicked problems, very little is available to how wicked problems (synonymous to ill-structured) should be formulated to make them well structured. Assessment of wickedness can help designers formulate problems into well-structured. This work proposes a metric for (lack of) structuredness as a measure for the degree to which a design problem is ill-structured. A Delphi-based method as benchmark for validating the metric is also proposed.

Keywords: design process, problem solving, wickedness, ill-structured, structuredness

1. Introduction

Design involves identifying problems from stakeholders in the form of needs and requirements and solving them (Pahl and Beitz, 1996). The process involves four broad stages: Task Clarification, Conceptual Design, Embodiment Design, and Detail Design. Problems primarily lie in the Task Clarification stage (Pahl and Beitz, 1996; Ulrich and Eppinger, 2003; Roozenburg and Eekels, 1995). Design Problems are initially ill-structured i.e., some of the goals, criteria, and constraints are unknown or unclear when given to the designers to solve (Dorst, 2003). Task Clarification is the stage in which ill-structured problems are translated into well-structured problems to better understand them. Problem understanding plays a key role in problem-solving (Eder, 2008). Researchers have identified many characteristics of ill-structuredness (Rittel and Webber, 1984 & 1973; Farrell and Hooker, 2013). In literature, wicked problems are taken to be synonymous with ill-structured problems (Rittel,1973; Peters, 2018) and are characterized by three parameters: 'system complexity', i.e., how complex the system is which has problems; 'agent finitude', i.e., how resourceful the agent is in solving those problems; and 'problem normativity', i.e., how motivated or interested the agent and society are in solving the problems (Farrell and Hooker, 2013). Wicked problems are a class of social system problems where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing (Churchman, 1967). Unlike linear models where solutions can be determined easily, wicked problems approach follows an indeterminacy which leads design problems to be wicked (Rittel and Webber, 1973). Neither those studying wicked problems nor others have attempted to answer the question as to why design problems are wicked. So, the wicked problem approach has remained only a description of social reality of designing rather than the beginning of a grounded theory of design. Also, design briefs are difficult to describe, synthesize, and standardize (Buchanan, 1992; Cross, 1982). The work presented in this paper proposes a measure of wickedness that intends to answer the above question.

2. Literature review

2.1 Understanding design problems and their formulation

Literature proposes various definitions and characteristics of a design problem. According to (Pahl and Beitz,1996), a design problem has three components - an undesirable initial state: i.e., the existence of an unsatisfactory situation; a desirable goal state: i.e., the realization of a satisfactory situation, and obstacles that prevent a transformation to happen from the undesirable initial state to the desirable goal state at a particular point of time (Pahl and Beitz, 1996). In a design process, Problems get translated via needs to requirements which can be technical, functional, aesthetic, etc.

Most of the literature takes requirement as an expression of what a design should have at a level of abstraction (Nidamarthi and Chakrabarti, 1997). These requirements are translated into ideas or solutions later in the process. Formulating a problem statement is a challenging cognitive task due to many reasons; it requires organizing the problem in terms of objectives, constraints, functions, and assumptions which are to be expressed in engineering requirements (Dym, Little, Orwin & Spjut, 2009).

Design briefs serve as more than merely the transfer of information. The brief as a starting point document serves the purpose of directing the design efforts (Koronis, 2019). It can serve as a point of reference that can be used to evaluate the outcome of the project (Bogers, 2008). Based on the current efforts in design research to understand the process of design briefing we can note its importance and influence in determining the later stages involving creative search for solutions (Baer, 2013; Blyth and Worthington, 2010; Paton and Dorst, 2011; Volkema, 1983). However, in practice, it remains a hard task. One reason for this difficulty is that design problems are largely ill-structured (Buchanan, 1992; Cross, 1982; Simon, 1973). This means the problem is not fully known making it harder to describe and synthesize it in a single document. Another difficulty is that no design process is exactly the same and so design briefs are also not easily standardizable (Buchanan, 1992; Cross, 1982). Design problems are "indeterminate" and "wicked" because design has no special subject matter of its own apart from what a designer conceives it to be. The subject matter of design is potentially universal in scope because design thinking may be applied to any area of human experience. But in the process of application, the designer must discover or invent a particular subject out of the problems and issues of specific circumstances (Buchanan, 1992). In actual practice, the designer begins with what should be called a quasi-subject matter, tenuously existing within the problems and issues of specific circumstances.

2.2 Wickedness and its characteristics

According to (Rittel and Weber ,1973), wicked problems are characterized by the following – “There is no definitive formulation of a wicked problem; wicked problems have no stopping rule; solutions to wicked problems are not true or false but good or bad; there is no immediate or ultimate test of a solution to a wicked problem; every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error and every attempt counts significantly; wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions; nor is there a well-described set of permissible operations that may be incorporated into the plan; every wicked problem is essentially unique; every wicked problem can be considered to be a symptom of another problem; the existence of a discrepancy representing a wicked problem can be explained in numerous ways; the choice of explanation determines the nature of the problem's resolution; the planner has no right to be wrong”. In subsequent literature, (Farrell and Hooker, 2013) have tried to simplify the characteristics of wickedness using three parameters: "**system complexity”** : this captures the difficulties arising due to or faced in getting a problem decomposed into sub-problems, the size of the problem, the number of goals, the level of existing knowledge that the problem-solving agent has, and the number of couplings among the sub-problems have; "**problem normativity”:** this captures the agent's motivation in solving the problem, the available space for knowledge growth, and the societal constraints on the problem; and “**agent finitude”** : this captures the level of existing knowledge in solving the problem and the size of resources available for problem solving. In simple terms, wickedness is about how complex the system is that has the problems, how resourceful an agent is, and how motivated the agent and society are in solving the problems (Farrell and Hooker, 2013).

2.3 Summary of the literature

Problem definition and formulation lie in the Task Clarification stage. After the problem is clarified, it gets increasingly more specified and detailed as solution alternatives are explored and a particular one among these is selected to satisfy high-level requirements.

Based on the requirements, solutions at the systemic level are found, depending upon the kind of solutions at that systemic level more problems are identified, and these system-specific problems keep on increasing as one progressively generates concept, embodiment, and detailed designs (Pahl and Beitz, 1996). This is called "co-evolution", where the problem and solution become more specific to the system within which they operate (Nidamarthi and Chakrabarti, 1997; Dorst, 2001).

People have tried to support coevolution by identifying and solving solution-specific problems (Nidamarthi and Chakrabarti, 1997; Dorst, 2001; Martinec, 2020). However, the early design stage where the initial problem is transformed into a well-structured one, is not adequately explored. In particular, there is no assessment of the level of structuredness that seems to characterize how wicked a given problem is at any stage of its evolution.

3. Aim and research question

The objective of the research presented in this paper is to develop a method for assessing structuredness of a given problem statement at any stage of its development so that by assigning structuredness scores within a range, a design team is able to create a standardized way of communicating and assessing the complexity of the alternatives or versions of the problems they explore. This should enable more precise and data-driven analysis of the problems, making it easier to compare and evaluate different problem statements. Different individuals or teams should be able to use the same framework to assess problems, leading to more consistent evaluations while reducing subjective bias.

The intent is to help stakeholders, researchers, and designers to identify the level of complexity of a problem statement easily and quickly, which can inform resource allocation, project planning, and problem-solving strategies. If different stakeholders, such as designers, experts, and decision-makers, use the same framework, this should enhance communication among them and ensure everyone has a shared understanding of the problems.

Turning our attention to the existing research gap within this domain, it becomes evident that a critical aspect remains unaddressed – the evaluation of wickedness in design problems. There is an absence of methodologies for distinguishing between ill, moderately, and well-structured problem statements. This is captured in the research question below:

> *Q. How to assess the wickedness (lack of structuredness) of a problem statement?*

4. Research methodology

The research methodology adopted consists of a review-based Descriptive Study I (DS-I) and an initial Prescriptive Study (PS) of the DRM framework by (Blessing and Chakrabarti, 2009). An exploratory study has been performed with direct observation data collected from design processes carried out by the student projects under a given problem area in a master's level course in design thinking at a university in India. All participants worked were in the age group of 22-24, had a Bachelor's or Master's in engineering or architecture with 0-2 years of work experience, and worked in groups of four to five to understand and solve the problems. The data obtained from these projects contains the initial briefs.

The research methodology also includes a comprehensive evaluation, of the proposed measure for assessing structuredness of design problems, sourced from various online platforms, patents, and other resources. Design briefs are diverse in their format, length, and content. The methodology that was used in this study can be described as an abductive approach in which a set of characteristics, identified from an analysis of problem formulation and problem-solving activities in empirical studies of design processes, were identified and applied on each brief to classify them using these characteristics.

5. Proposed metric for assessing structuredness

This assessment proposed below is intended to serve as an indicator of the complexity of a design problem, as to how 'wicked' the problem is. The research builds upon the established design process as outlined by (Pahl & Beitz, 1996) and focuses primarily on the requirement analysis during task clarification. The proposal is to express a design problem in terms of four related parameters: high-level requirements, low-level requirements, assumptions, and the connections that link these together. High-level and low-level requirements, organized within a specific hierarchical framework, represent the essential conditions that need to be satisfied.

In this hierarchy, fulfilment of low-level requirements is intended to be the means for satisfying the high-level requirements. Assumptions play a critical role in this process, representing statements that are considered true or anticipated to occur but have not yet been verified or substantiated. Assumptions arise due to various factors, such as limited knowledge, the need to standardize problem-solving approaches, the preference for general statements over specific ones, ambiguities in requirements, rules, and norms, as well as cultural influences and pressures (Addanki, Cremonini, and Penberthy, 1989). Assumptions are those that are necessary for a low-level requirement to be able to satisfy a high-level requirement. The journey from a given problem brief begins with the translation of the brief into a coherent set of problems. These problems are then compared with one another for the identification of higher-level and lower-level goals in them. This initial translation is followed by a more detailed analysis, wherein the goals are further categorized into high-level and low-level requirements and are mapped into a cause-effect diagram through root cause analysis. Root causes are found using various methods from the literature, such as the 'Ishikawa fishbone diagram', '5 Why techniques', 'tree analysis', etc. (Ishikawa, 1976). This leads to the formation of a hierarchical mapping of requirements. It is important to recognize that some of these requirements can serve as causal factors, triggering a chain or network of effects in relation to other requirements. In our specific case, each pair of high- and low-level requirements derived from a particular brief serves as a focal point for our assessment, see Figure 1.

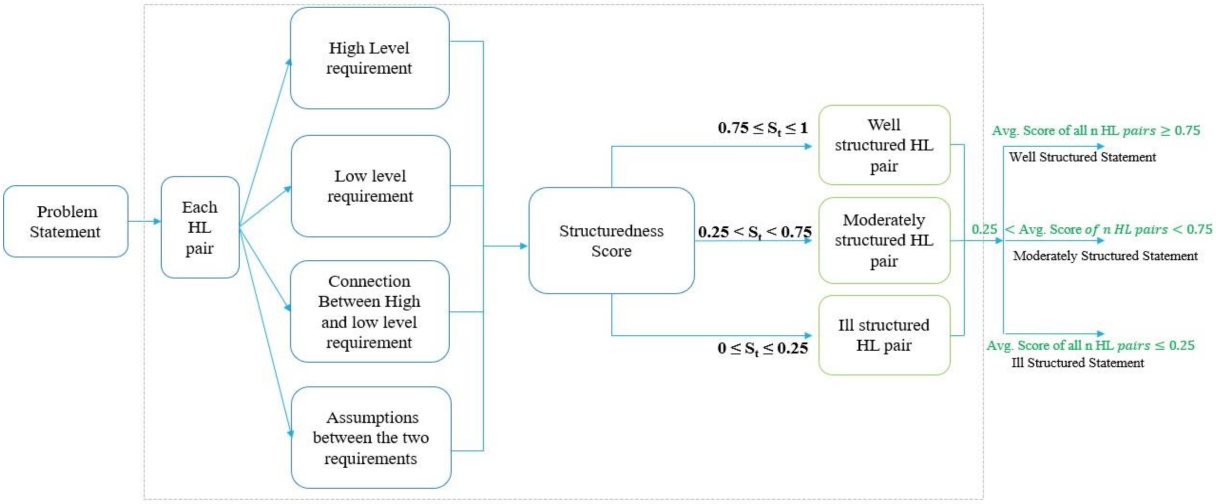


Figure 1. Translation of problem brief into a set of requirements and four variables along with metric for structuredness

The key variables under consideration are categorized as follows: High-level requirements (H), Low-level requirements (L), the Relationships (R) existing between two requirements, and the Assumptions (A) that underlie the connections between requirements within a particular set of HL pair. Our objective is to ascertain the overall degree of structuredness of a given problem brief, thereby determining how ill- or well-structured the problem brief or problem statement is. The categorization of score ranges and their corresponding problem types are mentioned below under different clauses and sub-clauses:

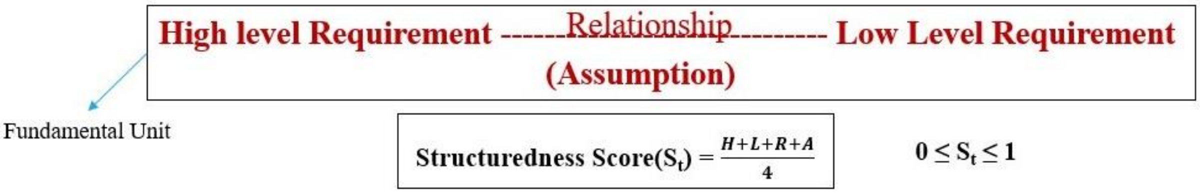


Figure 2. Fundamental unit describing the representation of four variables in a single HL pair

(A) For a set of High-level Requirement–Low-level Requirement pair (HL Pair) as described in Figure 2 in a problem statement, scores are assigned as follows:

(A.1) If a high-level requirement is present (more than one time, it is counted as one), then the value for H = 1; otherwise, H = 0.

(A.2) If a low-level requirement is present (more than one time, it is counted as one), then the value for L = 1; otherwise, L = 0.

(A.3) If a relationship between the two is present (more than one time, it is counted as one of a similar type), then the value for R = 1; otherwise, R = 0.

(A.4) If an assumption in the connection between the two is present (more than one time, it is counted as one of a similar type), then the value for A = 1; otherwise, A = 0.

For instance, if a low-level requirement is a direct cause for bringing the effect in the form of high-level requirement, then they appear to be directly connected hence values of H, L, R will be 1 and if they are supported by an assumption then value of A will also be 1.

And if the requirements are indirectly connected i.e., one may not be a direct cause for bringing the required effect then their R value will be taken as 0.

(B) ***If there are "n" number of HL pairs in a particular problem statement then initially for each HL pair:***

(B.1) If score ranges in (0, 0.25); then it is defined as ill structured HL pair.

(B.2) If score ranges in (0.25, 0.75); then it is defined as moderately structured HL pair.

(B.3) If score ranges in (0.75, 1); then it is defined as well structured HL pair.

(C) ***After determining scores from each pair, those will be averaged for overall structuredness score of a problem statement. Now,***

(C.1) If average Structuredness score of n HL pairs is less than 0.25 then the statement containing them will be ill structured statement.

(C.2) If average Structuredness score of n HL pairs is in the range of (0.25,0.75) then the statement containing them will be moderately structured statement.

(C.3) If average Structuredness score of n HL pairs is more than 0.75 then the statement containing them will be well structured statement.

For instance, $Average\ Score\ of\ n\ HL\ pairs \leq 0.25$, *It is an Ill Structured Statement.*
$Average\ Score\ range\ \ 0.25 < n\ HL\ pairs < 0.75$, *It is a Moderately Structured Statement.*
$Average\ Score\ of\ n\ HL\ pairs \geq 0.75$, *It is a Well-Structured Statement.*

For the proposed metric, the first step involves the extraction of HL pairs from a given problem statement, with a subsequent calculation of the structuredness score specific to each pair. After assigning a score to each individual pair in the problem statement, these scores are aggregated into a comprehensive structuredness score for the entire problem statement. The proposed structuredness assessment metric can be applied to each problem statement within the a given problem domain, or across problem domains. The computation of individual and overall structuredness scores is depicted in the case study below.

6. Case study demonstrating application of assessment metric

To demonstrate the application of the proposed metric, the problem area of waste management is taken (the area in which the students work in the design projects). The problem brief is stated as follows:

> *"The waste bins are used, they become dirty, which makes it harder to use these bins, leading to littering on or around the bins, which makes harder to use the bins leading to even more littering around. This also attracts dogs and other animals, leading to further littering and so on."*

A high-level problem of littering was identified from the given problem brief, and an analysis of its causes was carried out, see Figure 3.

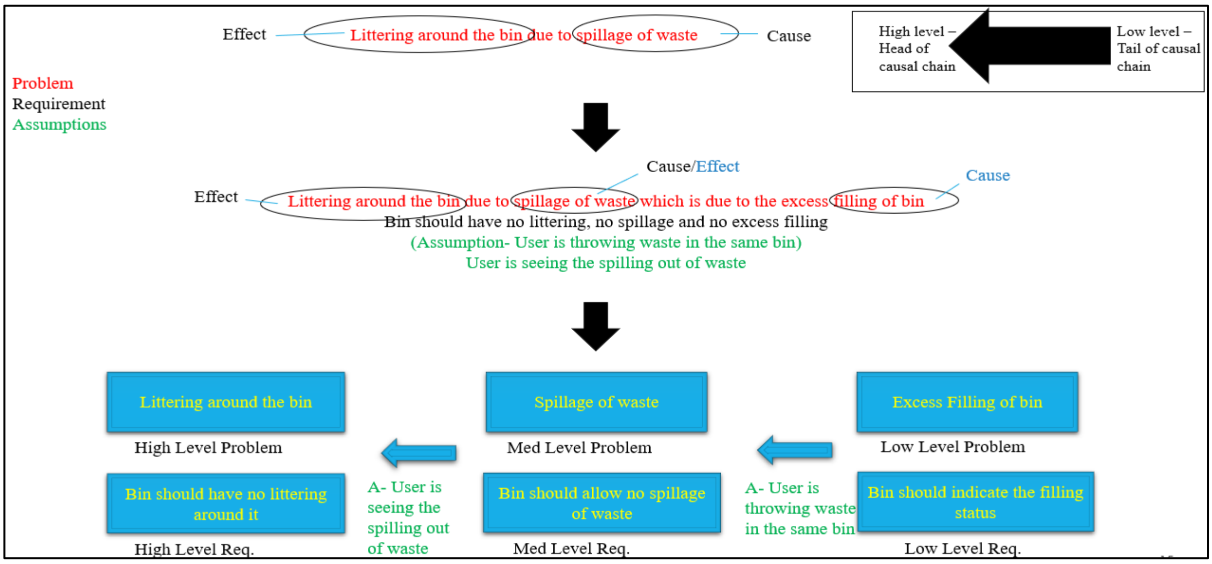


Figure 3. Cause and effect identification for high-level and low-level problem requirement pairs

The statements in red are problems, the ones in black are requirements, and those in green are assumptions associated with the high-level and low-level problem-requirement pairs. A requirement pair is described by the thick black arrow, the tail of which points to the low-level requirement (the cause), while the head points to the high-level requirement (the effect).

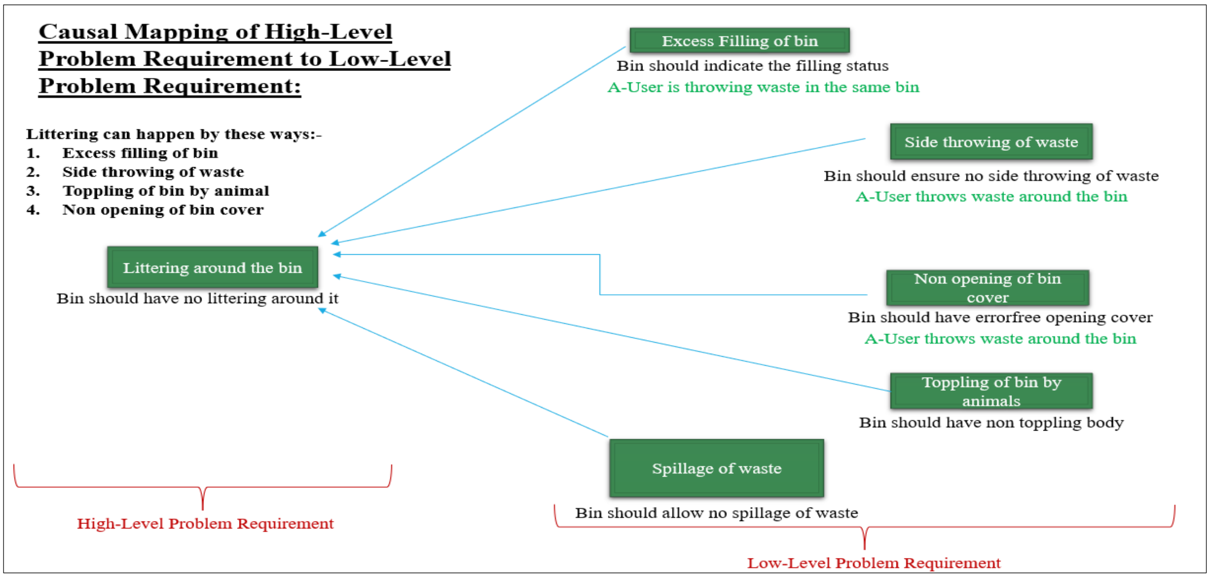
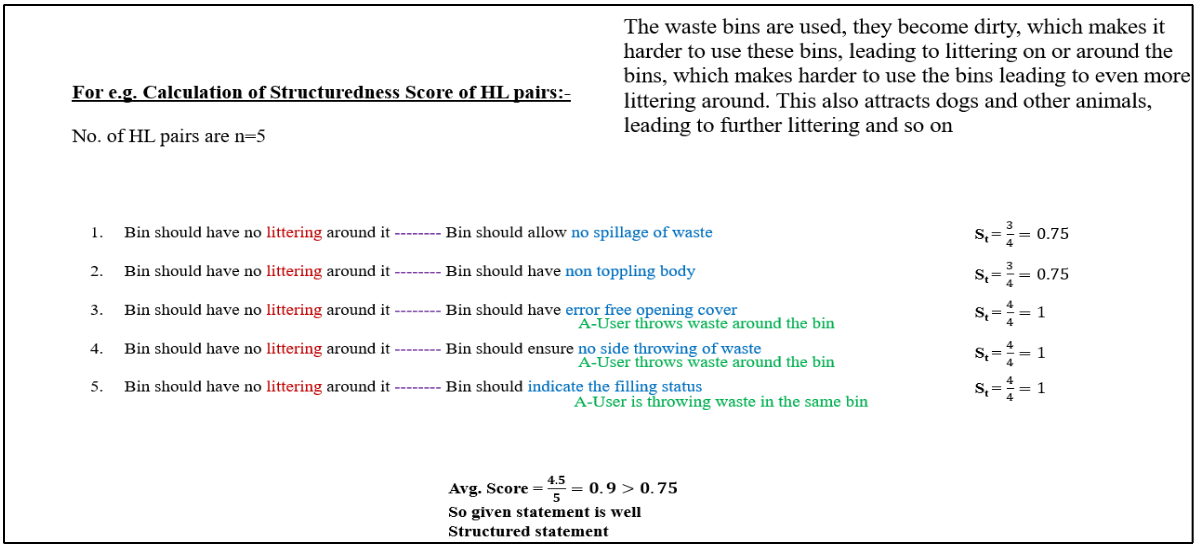


Figure 4. Causal chain between high-level-low-level problem requirement pairs

For instance, “Littering around the bin” is caused by “spillage of waste," which is caused by “excess filling of the bin." Further, “excess filling of the bin” cannot cause “spillage of waste” if the assumption “user is throwing waste in the same bin” is not true. Likewise, other root causes have been identified for “littering around the bin,” and they have been mapped, as shown in Figure 4.

The left portion of Figure 4. depicts the high-level problem requirement, while the right portion depicts the low-level problem requirement, resulting in high-level and low-level problem requirement pairs (HL pairs). As mentioned before, the head of the causal chain is called a high-level requirement, and the tail is called a low-level requirement. The HL pairs have been taken along with assumptions.



For e.g. Calculation of Structuredness Score of HL pairs:-

No. of HL pairs are n=5

The waste bins are used, they become dirty, which makes it harder to use these bins, leading to littering on or around the bins, which makes harder to use the bins leading to even more littering around. This also attracts dogs and other animals, leading to further littering and so on

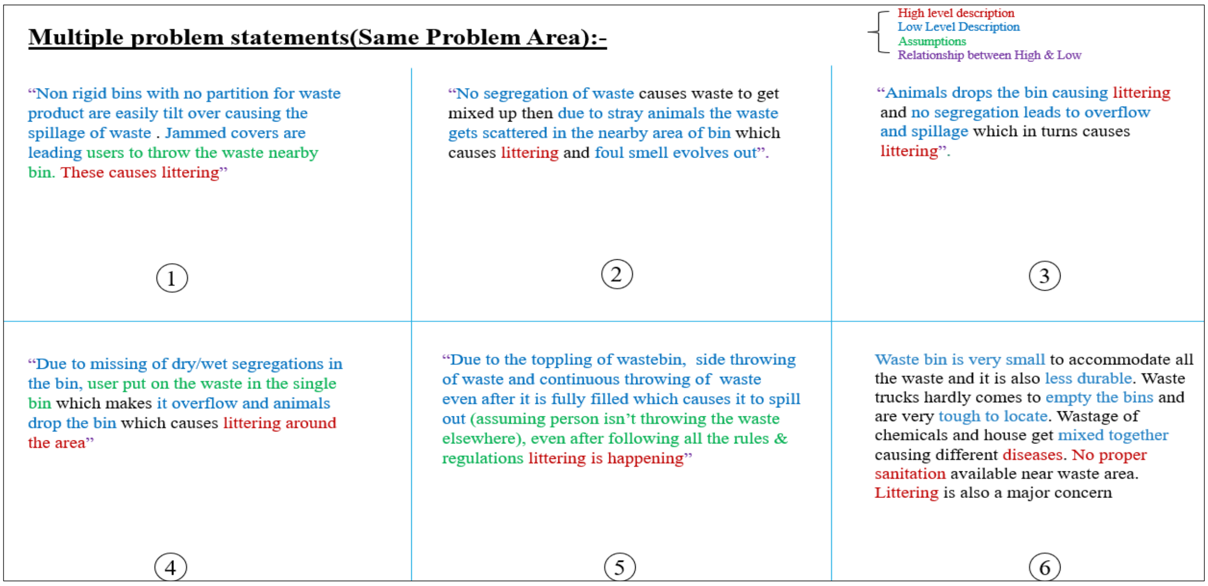
1. Bin should have no littering around it -------- Bin should allow no spillage of waste $S_t = \frac{3}{4} = 0.75$
2. Bin should have no littering around it -------- Bin should have non toppling body $S_t = \frac{3}{4} = 0.75$
3. Bin should have no littering around it -------- Bin should have error free opening cover $S_t = \frac{4}{4} = 1$
   A-User throws waste around the bin
4. Bin should have no littering around it -------- Bin should ensure no side throwing of waste $S_t = \frac{4}{4} = 1$
   A-User throws waste around the bin
5. Bin should have no littering around it -------- Bin should indicate the filling status $S_t = \frac{4}{4} = 1$
   A-User is throwing waste in the same bin

Avg. Score $= \frac{4.5}{5} = 0.9 > 0.75$

So given statement is well
Structured statement

Figure 5. Sample calculation of structuredness score for a problem statement

As shown in Figure 5, there are five HL pairs for the example problem statement. For each pair, an assessment of structuredness is carried out using the structuredness metric proposed in Section 5 and in Figure 1; the individual scores are depicted in Figure 5. The average of the scores of individual HL pairs is taken as the overall structuredness score for the whole problem statement. Since this score falls within the range of 0.75 to 1, according to the proposed metric that the overall statement is well-structured, displaying a high level of clarity and organization in its requirements.



Multiple problem statements(Same Problem Area):-

High level description
Low Level Description
Assumptions
Relationship between High & Low

①
“Non rigid bins with no partition for waste product are easily tilt over causing the spillage of waste . Jammed covers are leading users to throw the waste nearby bin. These causes littering”

②
“No segregation of waste causes waste to get mixed up then due to stray animals the waste gets scattered in the nearby area of bin which causes littering and foul smell evolves out”.

③
“Animals drops the bin causing littering and no segregation leads to overflow and spillage which in turns causes littering”.

④
“Due to missing of dry/wet segregations in the bin, user put on the waste in the single bin which makes it overflow and animals drop the bin which causes littering around the area”

⑤
“Due to the toppling of wastebin, side throwing of waste and continuous throwing of waste even after it is fully filled which causes it to spill out (assuming person isn’t throwing the waste elsewhere), even after following all the rules & regulations littering is happening”

⑥
Waste bin is very small to accommodate all the waste and it is also less durable. Waste trucks hardly comes to empty the bins and are very tough to locate. Wastage of chemicals and house get mixed together causing different diseases. No proper sanitation available near waste area. Littering is also a major concern

Figure 6. Multiple problem statements along with the four variables highlighted

Likewise, assessments have been carried out for other problem statements developed in the projects, each yielding distinct results. Among the six problem statements in Figure 6, Problems 1 and 2 have been assessed to be moderately structured statements, signifying a moderate level of clarity and organization in their requirements. On the other hand, Problem 6 has been deemed as an ill-structured statement, indicating a high degree of complexity and a lack of clarity in its requirements.

7. Empirical validation

Where experts are available in the domain of interest, a common approach for validation has been to use their collective opinions. For instance, (Sarkar and Chakrabarti, 2011) used the above to validate their proposed measures for novelty, usefulness, and creativity of designs. In general, the use of consensus of a panel of experts as benchmark is formalised in the Delphi method (Okoli and Suzzane, 2004; Schroda, 2000), which is used extensively for evaluation of various hypotheses. While empirical validation remains a part of our future work, the following using Delphi method is proposed as our approach for empirical validation of the proposed metric.

To evaluate the validity of the proposed structuredness metric, the approach is depicted in Table 1. The approach proposes to use the four parameters proposed by Farrel and Hooker (2013), see Section 2.2: the number of goals, difficulty in decomposition, social constraints, and the size of the problem. Given that there is no basis for assuming different weights for these parameters, a uniform weightage is assumed for all of them. For a given problem statement and associated requirements, each expert in a panel will be asked to give their qualitative assessment for each of these four parameters: (high or low for the Number of goals; high or low for Difficulty in decomposition into sub problems; high or low for social constraints; and high or low for Size of problem). High levels of all four parameters correspond to ill-structuredness and hence given a value "0"; low levels of all four parameters correspond to well structuredness and hence given a value "1". The average of the scores given by all in the pool of experts for each parameter are averaged to compute the overall score of structuredness as the benchmark. These scores for a series of alternative problem statements evaluated will be subsequently compared with their corresponding structuredness scores assigned using the proposed metric (as described in the earlier sections of the paper). The correlations between these two sets of scores would be used as an indication of the validity of the proposed structuredness metric. The conclusions to be drawn from the 16 possible combinations of values from experts and their respective decisions are outlined in Table 1 below.

Table 1. Benchmark using expert opinions for validating structuredness metric

Parameters/ Nature of statement	No. of goals (High=0; Low=1)	Difficulty in decomposition (High=0; Low=1)	Social constraints (High=0; Low=1)	Size of problem (High=0; Low=1)	Avg. Score: Average of the four parameter values (0-1)	Cumulative Decision: Ill (<0.3); Well (>0.7); Moderate (in-between)
Ill Structured	High (0)	High (0)	High (0)	High (0)	<0.3	Ill-structured
Moderately Structured	-	-	-	-	0.3<Avg.<0.7	Mod- structured
Well Structured	Low (1)	Low (1)	Low (1)	Low (1)	>0.7	Well-structured
Case 1	Low	Low	Low	High	0.75	Well-structured
Case 2	Low	Low	High	High	0.5	Mod- structured
Case 3	Low	High	High	High	0.25	Ill-structured
Case 4	High	High	High	High	0	Ill-structured
Case 5	High	High	High	Low	0.25	Ill-structured
Case 6	High	High	Low	Low	0.5	Mod- structured
Case 7	High	Low	Low	Low	0.75	Well-structured

Case 8	High	Low	High	Low	0.5	Mod- structured
Case 9	High	Low	High	High	0.25	Ill-structured
Case 10	Low	High	Low	High	0.5	Mod- structured
Case 11	Low	High	Low	Low	0.75	Well-structured
Case 12	Low	High	High	Low	0.5	Mod- structured
Case 13	Low	Low	High	Low	0.75	Well-structured
Case 14	Low	Low	Low	Low	1	Well-structured
Case 15	High	High	Low	High	0.25	Ill-structured
Case 16	High	Low	Low	High	0.5	Mod- structured

8. Summary, discussion and conclusions

With the intent of supporting the systematization of the process of structuring ill-structured problems into well-structured problems during the design process, this work proposed a metric for (lack of) structuredness as a measure for the degree to which a design brief is ill-structured. A major contribution of this work, we argue is that with the help of the proposed metric, a design problem statement for any design process is possible to be standardized. The central element in this metric is the high-level-low-level (HL) pairs that underly the problem brief and how well-structured (i.e., how causally connected and validated by data and reasoning) these pairs are. With this as the basis, a framework has been proposed for assessing structuredness. The expectation is that the metric would be used to assess how ill-structured a problem is, how the problem can be made more well-structured, and when it has become adequately well-structured. The process uses four parameters - high-level requirements, low-level requirements, causal connections, and assumptions that provide the empirical basis for corroborating their connections. A Delphi-based method for validating the metric is also proposed, which uses the four parameters that, according to (Farrell and Hooker, 2013) underpin the ill-structuredness of a problem. The main contribution of this work is to enable designers, researchers, and stakeholders to have a consistent understanding of a design problem in terms of its level of structuredness.

It is worth noting that, in the context of this model, higher values of the structuredness score correspond to more well-structured problem statements supported by the fact that if most of the variables (out of 4) are present then it describes the statement better, signifying higher levels of clarity and organization in their requirements. Conversely, lower scores indicate that the problem statements are more ill-structured, suggesting a greater degree of complexity and deeper a lack of clarity in their requirements.

A current limitation of the work is lack of validation of the proposed metric, which constitutes part of our future work. This would involve an assessment by a panel of domain experts of a series of alternative problem briefs, associated requirements and supporting information in that domain using the proposed Delphi-based method. This would be followed by correlation of the expert assessments with those obtained using the metric. A high correlation should indicate a corroboration of the empirical validity of the proposed metric for structuredness. Further work involves use of the metric in design processes to improve clarification of task, especially for ill-structured design problems, during the design process.

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