Chapter 7
System-Environment View in Designing

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Abstract A system interacts with its environment to satisfy requirements. Therefore, designing should involve developing the concept of both the system and its surrounding. A comprehensive review of literature on designing to analyse the use of system-environment view in designing revealed that while the concept of systems is used, implicitly or explicitly, by many design models, the concept of environment is rarely used as an evolvable construct in designing. Based on this, a system-environment view has been proposed in this paper that consists of: System, Subsystem, Elements, Environment and Relationships; each of these constructs is explicit and evolvable during design. The proposed system-environment view is empirically validated using protocol studies of design sessions, which were undertaken before this view was developed. The validation involved checking whether or not all the constructs in the system-environment view are naturally present, in these design sessions. An example of system-environment co-evolution during designing is also presented to show the importance of environment as an explicit evolvable construct in designing.

7.1 Introduction

A system interacts with its environment in order to satisfy requirements of the system and its environment. Therefore, developing the concepts of both the system and its environment are important in designing. Various researchers, e.g. [1-4] considered the interactions between system and environment as an important aspect of designing.

Asimow explained in detail the various interactions between engineering systems and their environment [1]. Deng et al. [2] showed that information of 'working environment' is useful for exploration of functional design solutions. According to Hall [3], physical systems not only exist in environment but they exist by means of an environment. Hubka and Eder [4], in 'Theory of Technical Systems',

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defined environment and discussed specifically about 'active environment', the portion of the environment that directly interacts with the system and plays an important role in the performance of the system.

While the primary focus of designing is to develop a system, environment must also be identified, specified, and variously modified, in order to ensure that they together are capable of fulfilling the requirements. Due to the primary focus of designing on the system, current literature on design theories, models and approaches either completely ignores this system-environment view – the perspective of taking both system and environment as explicit constructs – or focuses only on the system as the evolving construct during designing.

Henceforth in this paper, the system-environment view considers – system, sub-system, elements, relationships and environment, to help explain or design the interactions among them and the system-environment co-evolution.

The need for a system arises from its environment. As system is developed, its environment also gets modified. Hence, any changes in a system lead to change in its environment. There are various examples in literature on the evolution of products, where changes in a system have led to changes in its environment, and vice-versa. An example is the historical evolution of writing devices from the likes of pen and inkpot, in which design efforts variously focused on: either the pen as the system to be designed with the inkpot being given and hence part of the environment, or the inkpot as the system to be designed, with the pen being part of the environment. Subsequently, the two were considered together, leading to design of integrated pen and inkpot systems, such as a fountain pen or a ballpoint pen [5]. Another example is design of material handling robots such as pick-and-place robots. For these robots, the environment should also be designed, such as the locations of pick-up and place-down, the path of the robot and so on, in addition to the design of the robot in order to satisfy the task that the robot has to perform [6].

Therefore, we argue that a system-environment view must consist of explicit constructs to represent both the system and its environment, and must be incorporated into design theories, models and approaches as constructs that can evolve during design.

The specific objectives in this paper are:

1. To check if current literature on design theories, models and approaches uses the system-environment view in designing.
2. To propose a new system-environment view.
3. To check if the constructs of the proposed system-environment view are used naturally in designing.

7.2 Literature Survey

Various design theories, models and approaches are reviewed to investigate whether and how these take into account a system-environment view.

In Cross [7], VDI 2221 [7], Visser [8], Ulrich and Eppinger [9], the problems are divided to sub-problems for which sub-solutions are found and are combined to produce solutions. This can be perceived as a system-environment view at the level of problems and solutions but without the environment and relationships.

The outcomes of designing in French [10] are the selected schemes, general arrangement drawings, and part drawings. The selected schemes are at system level, general arrangement drawings are at subsystem level, and part drawings are at element level. In Cross [7] the outcomes are solution space, concept sketch, drawings, evaluated drawings, and final production documents. The solution space, concept sketch are at system level, drawings and evaluated drawings are at subsystem level, and final production documents are at element level. In Chakrabarti et al. [11], the outcomes are functions, solution-principles and embodiment. Functions are represented using input-output description and solution-principles are represented by stringed laws and effects. The input-output descriptions are either at system or at element level. The individual laws and effects are at the element level; these are strung together to form the system level description. Srinivasan and Chakrabarti [12] used the concept of system and environment to define the various constructs of the outcomes of the SAPPhIRE model. However, they did not explicitly use the concept of system-environment in their integrated model of designing.

Some researchers used system hierarchy structures to represent the system-environment view. Lossack [14] used task structure, physical principle structure and geometry structure. Pahl and Beitz [15] used function structure, working principle structure, assembly drawings and so on. VDI 2221 [7] used function structure, module structure and so on. Cross [7] suggested the use problem structure and decision trees. Similarly, Ulrich and Eppinger [9] suggested the development of hierarchy of needs, in the concept development phase of design. In these researches, system-environment view had been used at several levels of abstraction without considering environment.

Hubka and Eder [4] developed a theory of technical systems. Their system-environment view consists of system, subsystem, elements, components, relationships, environment, and active environment. However, neither ‘environment’ nor ‘active environment’ is used as an evolvable construct in designing. They used system hierarchical structures at different levels of abstraction e.g. transformation process structure, function structure, organ structure, and component structure [17]. Hansen and Andreasen [13] developed the domain theory based on systems theory and therefore implicitly considered system-environment view. In domain theory, there are three main domains: transformation, organ and part. Domain theory and Hubka’s function-means law were combined [13] and function-means law was modeled as a tree structure; it is set-up as a function/means tree which is a hierarchical arrangement of functions and means that are connected by causal relationships. The function/means tree represents the system view in this approach.

Hall [3] used a system-environment view that consists of system, subsystem, objects, relationships and environment. Hall considers environment as a major factor in the design process, and hence used ‘initial environment’ and ‘final environment’ in his model of the systems engineering process; however, he did not use ‘environment’ as an evolvable construct during the process.

Asimow [1] and INCOSE [16] used system-environment view explicitly without considering the environment. Asimow [1] in his morphology of design proposed using system, subsystem, components and parts. Although he considered the interactions between system and environment as important, environment was not used as an evolvable construct in his model of designing. INCOSE [16], for the systems engineering process, uses a view with these constructs: system, element or segment, subsystem, assembly, subassembly, components and parts. Ulrich and Eppinger [9] in the system level design explicitly used a system-environment view (without considering environment); in this view, the product is divided into functional and physical elements. Functional elements of a product consist of individual operations and transformations. Physical elements of a product are parts, components and subassemblies.

Howard et al. [18] explicitly used modular hierarchical structures to represent the system-environment view without considering the environment. Blessing [19] used product model (which consists of product, assemblies, components and standard components) to represent the system-environment view without considering the environment. Prabhakar and Goel [20] proposed Environmentally-driven Adaptive Modelling (EAM), which uses Environmentally-bound Structure-Behavior-Function [ESBF] model. ESBF model supports a hierarchy of interactions between a device and its environment. In Environment based Design (EBD) methodology by Zeng [22, 23] defines *product system* as “the structure of an object (Ω) including both a product (S) and its environment (E)”. EBD uses a hierarchical representation in which system and environment are connected to each other via a set of objects. Zeng states that, “in the design process, any previously generated design concept can be treated as an environment component for the succeeding design, as a result, a new state of design can be defined as the structure of the old environment (Ei) and the newly generated design concept (Si), which is a partial design solution”. This change in the state of the environment, where the new environment consists of the earlier environment plus the new design, is proposed as “evolution of environment”. However, this work does not propose system-environment *co-evolution* as proposed in our paper. This is because Zeng considers system and environment to be mutually exclusive [23]; therefore, the new environment, created by adding a change in the system, amounts to changing either the system or its environment, but *not both and not together*.

Relationships – one of the constructs of the system-environment view – are considered explicitly by Hall [3], Hubka and Eder [4], Blessing [19], and Bhatta and Goel [21]. Hall [9] stressed that relationships is what “makes the notion of ‘system’ useful” Hubka and Eder [4], in their system-environment view, define relationships of various types e.g. analogy, homomorphy, isomorphy, equivalence, identity, causality, coupling, goal-means, spatial and logical. Blessing [19] uses a relationships model, which contains several relationships (e.g. spatial, functional and hierarchical). The structure of a device in the SBF model of Bhatta and Goel [21] is represented hierarchically in terms of its constituent structural elements and relations among them such as part-of, includes and parallely-connected. Lossack [14], and Pahl and Beitz [15] consider connections or interrelationships using system hierarchy structures. Chakrabarti *et al.* [24] developed a SAPPhIRE model of causality; according to it: parts create organs. The relevant input and organs together activates a principle (effect), which in turn creates phenomenon. Phenomenon changes the state of the system and its environment (state change), which can be interpreted at a higher level of abstraction (action). Here creates, activates, changes, and interpreted, as are the causal relationships among the outcomes.

The following points are concluded from the above review of literature:

1. Only some researchers consider the system-environment view. Very few consider the system-environment view explicitly (e.g. Hubka and Eder [4, 17], Hall [3]); others consider this view implicitly (e.g. Hansen and Andresen [13]). Most of these researchers do not consider environment.
2. Relationships are explicitly considered in very few theories, models and approaches (e.g. Hall [3], Hubka and Eder [4], Blessing [19], Bhatta and Goel [21]); the rest consider it implicitly (e.g. Lossack [14], Pahl and Beitz [15]).
3. Environment is explicitly considered in very few theories, models and approaches, e.g. Deng et al. [2] and Hubka and Eder [4].
4. None of the models consider 'environment' (that is universe without the system) as an evolvable construct in designing. Consequently, none of the models note the occurrence of co-evolution of system and environment as a phenomenon during designing.

7.3 Proposed system-environment view

We propose the following system-environment view, which consists of the constructs: system, sub-system, elements, relationships and environment. Here both system and environment are evolvable constructs in the process of designing. These constructs are defined as follows. A system is the overall product being designed, at any level of abstraction. A sub-system is a subset of a system that can be further divided. An element is a subset of a system or a sub-system, which cannot be further divided. An environment refers to all subsets of the universe apart from the system. The relationships are how system, environment, sub-systems, and elements are linked with one another. Elements (and sub-systems) combine together to comprise sub-systems. All sub-systems and elements combine together to comprise the system. System is characterized by a system-boundary that separates it from the environment. System needs an environment (which is outside the system-boundary) to satisfy its requirements.

These constructs are illustrated with a ballpoint pen, which is a system made up of refill, body, and a cap. The refill is a sub-system consisting of elements like nib, ink and ink reservoir. The body is another sub-system consisting of elements like upper-body and lower-body. The environment for the ballpoint pen includes papers on which it has to write, and an agent that uses the pen to write on the paper. The above example is given only at the the physical structure level of abstraction; however, the system-environment view can exist at any other level of abstraction.

7.4 Validation of the System-environment View

In order to validate the importance of incorporating a system-environment view in design theories, models and approaches, we analysed video protocols from a series of design sessions to check if the constructs of the view are used in designing. Four designing sessions are used for validating the importance of system-environment view. The intent was to check whether or not these constructs of the system-environment view proposed are naturally used, albeit implicitly, in these design sessions. The video and audio protocols, their transcriptions, problem briefs, sketches of design session are taken from an earlier research [25], which was carried out before this view was developed.

Each design session consisted of an individual designer solving a design problem under laboratory conditions. The designers were trained and instructed to discuss-and-think-aloud. These design sessions were video and audio recorded and each session was assisted by a researcher for any clarification during the session. Four designers [D1-D4] of varying background and experience were each given one problem brief from among three product design problems [P1-P3], Tables 7.1 and 7.2.

Table 7.1 Pattern of Problem-Solving

Problem brief	P1	P1	P2	P3
Designer	D1	D2	D3	D4

Table 7.2 Pattern of Problem-Solving

	Problem-briefs
P1	India has large number of people with transferable jobs. They need to shift frequently from one place to other (every 1-2 years). And often face problems transferring present types of furniture, which are bulky and heavy. It is not economical for them to buy furniture and sell it before shifting to other place. This furniture occupies lot of space and this is an additional problem since they live in small houses. It takes more time to pack the furniture and it damages during transport if it is not packed properly. Your task is to design portfolio of furniture which will help in sleeping and storing things while taking into account the above problems mentioned. Setup time and effort on the part of user should be minimal
P2	India has large number of people with transferable jobs. They need to shift frequently from one place to other (every 1-2 years). And often face problems transferring present types of furniture, which are bulky and heavy. It is not economical for them to buy furniture and sell it before shifting to other place. This furniture occupies lot of space and this is an additional problem since they live in small houses. It takes more time to pack the furniture and it damages during transport if it is not packed properly. Your task is to design portfolio of furniture which will help in sit, write and eat while taking into account the above problems

mentioned. Setup time and effort on the part of user should be minimal.

P3 There are many problems associated with the increase in temperature during summer. Huge numbers of people die because of heat waves. A number of products are available such as umbrella and hat to help alleviate part of these problems; however, there are useful only for blocking the direct sunlight. These are not able to protect a person from high temperature and heat waves. Air conditioners are available and solve this problem; however, they are expensive and work only in fixed setting. No mobile and portable equipment is available that can be carried around while in transit. There is a need for a product that will help in maintaining body temperature within a comfortable range. Your task is to design a product that will help in solving these problems. It should help the user in avoiding direct sunlight and maintaining body temperature. The user should be able to use it with-out any difficulty in setup and it should be portable.

The transcriptions of these design sessions are analysed by coding the transcriptions using the following constructs, which together represent the system-environment view. The utterances of the designers from the transcription are used as instances of the above constructs (see table 7.3).

Table 7.3 Constructs of System-Environment view and instances from transcriptions

Sy-En view		Instances from designing sessions
System	Sy	D: "I have basic chair would be I am making one conventional chair which can help in sit, write and eat, that is somewhere near a dining table". [Episode: Designer develops a chair as a solution for all the given requirements (i.e. sit, write, eat, and easy to transfer). Therefore chair is a System]
Environment	Env	D: "I have basic chair would be I am making one conventional chair which can help in sit, write and eat that is somewhere near a dining table". [Episode: Designer develops a chair (System) as a solution for the given requirements under specified environmental conditions such as presence of a table for writing and eating.]
Subsystem	SS	D: "so it (System) again becomes something like a suitcase and plus this retractable lid which will have to be carried in the rectangular frame kind of thing". [Episode: Suitcase and retractable lid forms a subsystem as both together will be put in a rectangular frame together forming a system]
Elements	El	D: "Velcro strip that can rest on these supports". [Episode: Velcro Strip is an Element developed]
Relationships	Rel	D: inner diameter handles is 25mm which exactly matches with the outer dia of the tube [Episode: Here designer defines organ level relationship "equality constraint" between inner dia of handles and outer dia of tubes

Fig. 7.1 shows the frequency of the instances of each construct in each of the four designing sessions analysed. All the constructs of the proposed system-environment view are observed to have been used in natural designing.

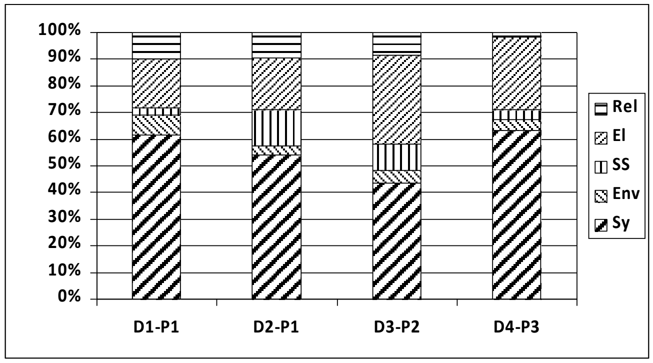

Fig. 7.1 Percentage of Constructs of the System-environment View in Design Sessions

7.5 Illustration of System-Environment Co-evolution

An example of the System-Environment co-evolution is taken from the session in which D1 solved P1. From the problem brief, D1 found various problems associated with the furniture [i.e., the Existing Systems], two of which are: 'space for furniture', 'unfolding and packing' as shown in Fig. 7.2.

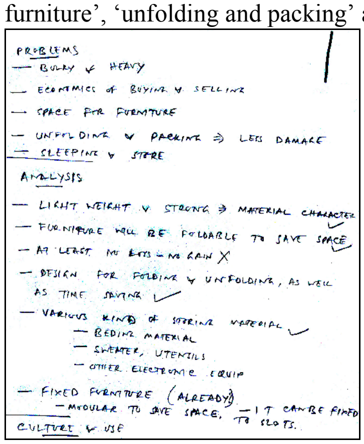

Fig. 7.2 Problems Identified by D1

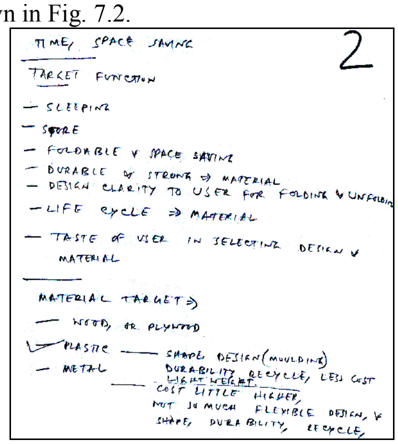

Fig. 7.3 Requirements Identified by D1

The problems identified were then evaluated and modified by D1, and requirements such as the following were generated: 'furniture will be foldable to save space' and 'fixed furniture (already)' [with the following sub points - 'modular to save space' and 'It can be fixed to slots'], as shown in Fig. 7.2.

From all the requirements generated, D1 made a list of requirements to be fulfilled by the system. One of these – 'foldable and space saving' – see Fig. 7.3.

With the above list, D1 sketched an idea of a piece of furniture (Sy), see Fig. 7.4. According to this idea, when the user needs to use the furniture (Sy) as a bed or a storage space, it would be horizontal, but when not in use, (Sy) could be folded against the wall (Env) to save floor-space (Env). To fold the furniture (Sy) against the wall (Env), D1 defined the distance between the furniture (Sy) and the wall (Env); he also defined the relationship between the furniture (Sy) and the floor (Env) as a 'hinge joint', as shown in Fig. 7.5.

This example illustrates that, as the design process progressed, both the system and its environment evolved, simultaneously and through mutual influence.

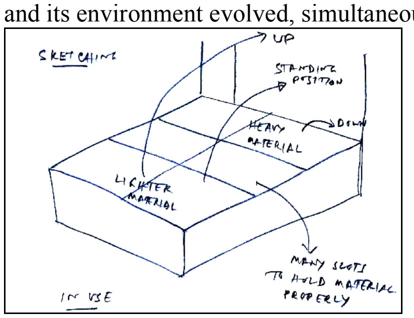

Fig. 7.4 One design Idea generated by D1

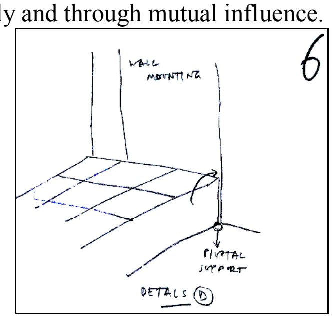

Fig. 7.5 Detailed Description of Idea in Fig. 7.4

7.6 Conclusions

The major findings in this work are as follows. Literature stresses the importance of the system-environment view, which includes environment as a construct, in designing. Current design models, however, do not consider environment as an explicit, evolvable construct in designing. Explicit representation of this view is necessary for describing system-environment co-evolution. Based on literature, a new system-environment view is proposed. Empirical studies show that designers consider both system and its environment as evolvable constructs, and change them as necessary during designing. Further, this work shows the presence of all the constructs of system-environment view in designing, and their co-evolution.

7.7 References

1. Asimow (1962), Introduction to design, Prentice-Hall Inc, Englewood Cliffs (NJ).
2. Deng Y.M., Tor S. B. and Britton G. A. (2000), Abstracting and Exploring Functional Design Information for Conceptual Mechanical Product Design, Engineering with Computers 16, Springer-Verlag London Limited, 36–52.
3. Hall A.D.(1962),A methodology for systems engineering,6th ed. Princeton(NJ),Van Nostrand.

4. Hubka, V. and Eder, W. (1988), Theory of technical systems, A Total Concept theory for Engineering Design, Springer-Verlag.
5. http://en.wikipedia.org/wiki/Pen
6. Groover, P. M. (2006), Automation, Production Systems and Computer Integrated Manufacturing, 2nd edn, Prentice-Hall Inc.,New Jersey, USA.
7. Cross, N. (2000), Engineering design methods–Strategies for product design, John Wiley and Sons, England.
8. Visser, W. (1991), Evocation and elaboration of solutions: Different types of problem solving actions, Proceedings of 3rd COGNITIVA symposium on at the crossroads of artificial intelligence, cognitive science, and neuroscience, Madrid, Spain, 161-168.
9. Ulrich K. T., Eppinger S.D. (2003), Product Design and Development, 3rd Edition, Tata McGraw Hill.
10.French, M. (1999), Conceptual design for engineers, Springer–Verlag, Berlin, Germany.
11.Chakrabarti, A., Johnson, A. and Kiriyama, T. (1997), An approach to automated synthesis of solution principles for microsensor designs, Proceedings of International Conference on Engineering Design (ICED97), Helsinki, Finland, 125–128.
12. Srinivasan, V., and Chakrabarti, A., (2010), "An Integrated Model of Designing", in Special Issue on Knowledge Based Design, ASME Journal of Computing and Information Science in Engineering (JCISE), Vol. 10, Issue 3, ed. by Ashok K. Goel and Andrés Gómez de Silva Garza, 031013.
13.Hansen, C. and Andreasen, M. (2002), Two approaches to synthesis based on the domain theory, In: A. Chakrabarti (ed) Engineering design synthesis – understanding, approaches and tools, Springer-Verlag, London, 93 -108.
14.Lossack, R. (2002), Design processes and the context for the support of design synthesis, In: A. Chakrabarti (ed) Engineering design synthesis – understanding, approaches and tools, Springer-Verlag, London, 213-227.
15.Pahl, G. and Beitz, W. (1996), Engineering design: A systematic approach, 1st edn, Spriger-Verlag, London, UK.
16.INCOSE (2004), Systems Engineering Handbook - a “What To” Guide for all se Practitioners, INCOSE-TP-2003-016-02, Version 2a, Released by - Technical Board, International Council on Systems Engineering (INCOSE).
17.Hubka, V. and Eder, W. (1996), Design Science: Introduction to the Needs, Scope and Organization of Engineering Design Knowledge, Springer-Verlag London Limited, Web Translation by W. Ernst Eder and Filippo A. Salustri.
18.Howard, T., Culley, S., Dekoninck, E. (2009), The integration of systems levels and design activities to position creativity support tools, In: Research into Design: Supporting Multiple Facets of Product Development, ICoRD’09, Bangalore, India, 43 -50.
19.Blessing, L. (1994), A process-based approach to computer-supported engineering design, PhD thesis, University of Twente, Netherlands.
20. Prabhakr, S. and Goel, A. (1998), Functional Modeling for Enabling Adaptive Design of Devices for New Environments. Artificial Intelligence in Engineering, Vol. 12, pp. 417-444.
21.Bhatta, S. and Goel, A. (2002), Design patterns and creative design, In: A. Chakrabarti (ed) Engineering design synthesis – understanding, approaches and tools, Springer-Verlag, London, 271-284.
22. Zeng, Y., (2011), Environment-Based Design (EBD) Methodology, ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Washington DC, USA, DETC 2011-48263.
23. Zeng, Y., (2004), Environment-based formulation of design problem. Transaction of SDPS: Journal of Integrated Design and Process Science, Vol. 8, Issue 4: pp. 45-63.
24.Chakrabarti, A., Sarkar, P., Leelavathamma, B. and Nataraju, B.(2005), A functional representation for aiding biomimetic and artificial inspiration of new ideas, Artificial Intelligence for Engineering Design,Analysis and Manufacturing(AI EDAM), Vol.19, Issue2, pp.113-132.

25. Kota, S. (2010), An interactive support for developing environmentally friendly product lifecycles, Ph.D. Thesis, Indian Institute of Science.