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A REVIEW ON INFORMATION IN DESIGN

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ABSTRACT

Independence of design, information and complexity are the basic concepts of Axiomatic Design. These basic concepts have proven to be generic; axiomatic design was successfully applied in many markets and on a broad range of products and services. Information, or entropy, plays a central role in Axiomatic Design. In this paper an attempt is made to organise the different kinds of information, understand them, and evaluate the consequences of the ways they can be applied. A number of six kinds of information are reduced to two most determining kinds of information for the design. Unorganised information is about choosing the right and independent design relations. Axiomatic information is about further optimisation of these design relations. This paper leads to the confirmation that axiom 1 & 2 are in fact corollaries of the complexity axiom that is constituted of the two kinds of information. Though this revises the foundation of Axiomatic Design, the operation and practical application are not much affected for a number of reasons. One of them is that a higher axiom does not alter the basic ideas behind Axiomatic Design; it remains axiomatic.

Keywords: Axiomatic Design, Information, Complexity, Independence, Entropy

1 INTRODUCTION

Independence of design, information and complexity are the basic concepts of Axiomatic Design (AD) as developed by Nam P. Suh and his team at the Massachusetts Institute of Technology (MIT). The basic concepts have proven to be generic: Having its origin in manufacturing, AD was successfully applied in many markets and on a broad range of products and services.

AD declares 'Axioms' that cannot be proven nor derived from physical phenomena. A number of seven conceptual axioms were defined back in 1978 when the first paper about AD was presented [Suh et al, 1978]. Only two of those seven axioms stood the test of time, now known as the 'Independence Axiom' and the 'Information Axiom'. In 1999 a third axiom was added, the 'Complexity Axiom', addressing four different types of complexity in design processes [Suh, 1999]. The general guideline of AD is that Functional Requirements (FRs) are satisfied by a sensible selection of Design Parameters (DPs), and the probability of this happening is a measure of success for the system design. The probability is a central theme around which the axioms are carefully wrapped.

The probability of DPs satisfying FRs, if not ideal (P<1), is a measure for information. Information or 'Entropy' is a state of chaos and, in good accordance with the nature of the specific axioms, it should be reduced. Depending on the kind of information, one of the three axioms and their underlying methods are applied to address the information as appropriate as possible. In this paper an attempt is made to organise the different kinds of information, understand them, and evaluate the consequences of their application. The relation between information and complexity is investigated.

This paper is organised as follows: In section 2 an evaluation is made of the current status of information and earlier investigations about the information as a function of the design matrix. Section 3 is inventories information within and just outside the framework of AD. Information is decomposed and visualised to show the relations between the different kinds. Section 4 discusses the findings and summarises conclusions.

2 INFORMATION AS A BASIS OF ALL AXIOMS

Information is mostly interpreted as transferred knowledge concerning a particular state or circumstance. Information in engineering is mostly related to the notion of complexity. If a system is complex, a lot of information is required to describe the system.

2.1 INFORMATION IN AXIOMATIC DESIGN

Information in Axiomatic Design is derived from the information technology using a logarithmic measure of entropy according to Hartley [Hartley, 1928] and Shannon & Weaver [Shannon & Weaver, 1949]. According to this theory, information is inversely related to the probability of success of a DP causing a FR to be within tolerances. The information axiom dictates that information content should be minimised, and thus maximising the probability of FRs to be satisfied. Suh describes two main types of information, 'Useful' and 'Superfluous' information. Useful information is information that affects FRs. Superfluous information does not affect the relation between DPs and FRs. Therefore, superfluous information is no information from the axiomatic perspective.

2.2 INVESTIGATIONS FOR THE INDEPENDENT BEHAVIOUR OF THE AXIOMS

The dependency of the Axioms has been investigated a number of times. The first book about AD [Suh, 1990:67] includes a paragraph about the relationship between axioms 1 and 2. Suh addresses the misunderstanding that the independence axiom is a 'consequence of the information axiom', by explaining that a coupled design could have lower information content than an uncoupled design. Without the independence axiom it is not possible to choose an uncoupled design, which, from the design perspective, is more preferred than a coupled design. A preferred sequence is proposed: 'first realise an independent design, before optimising it by reduction of the information content of that design'. The second book [Suh, 2001:175] contains some mathematical proof of the independence, based on the Bolzmann entropy of the FR array as was published by [El-Haik & Yang, 1999]. If the design matrix is square and non-singular with constant entries, and DPs are normally distributed random variables, the entropy h of the FRs is given by

$$h(f\{FR\}_m) = h(f_{DP}\{DP\}_n) + |lnA| \qquad (1)$$

where |A| is the determinant of the design matrix [A]m.n. Investigation of the determinant |A| leads to the understanding that a coupled matrix can indeed have a lower information content than an uncoupled matrix. Not specifically mentioned, but logically coming forth from the result, is the fact that uncoupled and decoupled matrices with the same diagonal elements have the same entropy and therefore have equal amounts of information. So a coupled matrix could lead to lower information than a decoupled or uncoupled matrix, which was reflected by the substantiation of corollary 7. The book of [El-Haik, 2005] confirms equation (1). Based on analysis of the design matrix, a coupled design could have lower information content and thus appear to be a better option. This is overruled by the independence axiom. Therefore, both axioms serve a particular goal and should be maintained.

2.3 INFORMATION AS BASIS FOR REAL COMPLEXITY

Complexity is defined as 'A measure of uncertainty in achieving the specified FRs' [Suh, 2005:4,58,65]. The Complexity Axiom advises to 'Reduce the complexity of a system'. The theory defines two kinds of complexity, time-independent and time-dependent. This paper is limited to time-independent complexity, which does not change with time. Time-independent complexity consists of two components: 'Real' and 'Imaginary' time-independent complexity, further to be referred to as real and imaginary complexity (C_R and C_{Im}).

Real complexity is inversely related to the probability of success that the associated FRs are satisfied according to one of the following relations

$$C_R = -\sum_{i=1}^{m} log_b P_i \qquad (2)$$

$$C_R = -\sum_{i=1}^{m} log_b P_{i|\{j\}} \qquad (3)$$

depending if the system is uncoupled (2) or decoupled (3). Relation (2) is under the reservation that the total probability P_i is the 'joint probability of processes that are statistically independent'. Relation (3), for decoupled systems, is modified to correct for dependencies in the probabilistic function [Suh 2005:57]. 'b' Is in both cases the base of the logarithm, usually in bits of nats according to the definition by [Hartley, 1928].

Given (2) and (3), real complexity can be related to the information content, which was defined in terms of the probability of success of achieving the desired set of FRs [Suh 1990:59], as

$$I = C_R \qquad (4)$$

2.4 INFORMATION AS BASIS FOR IMAGINARY COMPLEXITY

As explained in 2.3, information content I_i is defined in terms of the probability P_i of satisfying FR_i. In a system with more FRs, the joint probability of satisfying all FRs is applied. The question rises what is the relation between information and entropy to imaginary complexity.

2.4.1 CURRENT DEFINITION OF IMAGINARY COMPLEXITY

Imaginary complexity is defined as complexity that exists due to 'a lack of understanding about the system design, system architecture or system behaviour' [Suh, 1999:120]. It is caused by the absence of essential knowledge of the system. The designer cannot solve the problems in a structured manner and therefore is forced to apply trial-and-error. Imaginary complexity exists until understanding of the problem is acquired; it instantly and permanently disappears when the knowledge becomes present. Though the source of imaginary complexity, a trial-and-error process, can be stochastic, Suh never relates trial-and-error probabilities to information of any kind. Imaginary complexity is by definition not related to information in AD and trial-and-error probabilities will not increase the information content of a design. The motive for this choice was not found in Suh's work; it is basically a matter of definition.

2.4.2 BOLZMANN ENTROPY AS BASIS FOR IMAGINARY COMPLEXITY

As imaginary complexity does not lead to information as defined in the axiomatic context, a broader perspective could be applied. This perspective is based on two observations. First, the information theory of Shannon and Weaver, based on the Bolzmann entropy, is 'related to the number of alternatives that remain possible to a physical system' [Shannon & Weaver 1949:1]. It does not relate to what the design 'is' as much as what the design 'could be', being an amount of freedom of choice [Shannon & Weaver 1949:8,9]. In this case it points to the number of design outcomes as function of the stochastic variability in the design (design being the relation between FRs and DPs). The result of this observation is that, if the trial-and-error probabilities have a

stochastic nature, it increases the Bolzmann entropy. Secondly, the quality of a design never exceeds that of the designer. A 'good design' in the hands of an ignorant designer will not be recognised as such. Optimisations in the perception of the designer will lead to reinvention of the wheel; they might lead to a different good design, but could also degrade the level of the design. This observation leads to the belief that a design is only as good as the understanding of its designer. It cannot be assumed that an ignorant designer will produce a good design and the lack of knowledge, as a result, will cause an increase of the entropy in the design.
Based on these observations, trial-and-error probabilities should be considered to contribute to the entropy in the design.

The increase of entropy is analogue to an increase of the information content in the design. Note that this information is a different kind of information, not the same as defined for the information axiom in AD. Consequently, a new definition is needed to differentiate these two kinds of information. The entropy related to trial-and-error processes, provided that they are stochastic and independent, is analogue to real information defined conforming the method of Hartley and Shannon as

$$I_{UnOrg} = -\sum_{j=1}^{n} log_b\, P_j \tag{5}$$

where P_j is the joint probability caused by trial-and-error events taking place in the design process.

The information caused by trial-and-error processes is called 'Unorganised Information'. Unorganised information only exists if the design matrix has not been organised yet. When the design matrix is organised, by decoupling FRs and DPs, this kind of information will have disappeared completely. Unorganised information does influence the relation between FRs and DPs but has no impact on the common range of the system. As such, unorganised information is structurally independent from information as defined by the information axiom (further to be referred to as 'Axiomatic Information').

Though imaginary complexity was never defined specifically in terms of Hartley's logarithmic function, it was applied as such in [Suh, 1999:121] and [Suh, 2005:66]. By formalising this, imaginary complexity equals unorganised information as

$$I_{UnOrg} = C_{Im} \tag{6}$$

2.5 Magnitude of Axiomatic Information and Unorganised Information

The information content of real- and imaginary complexity are of a different magnitude [Suh, 2005:71]. A simple calculation example indicates what order of magnitude may be expected. If a system, with a uncoupled or decoupled design matrix has five FRs that are satisfied 95% of the time, the probability of satisfying all FRs and the axiomatic information content could be calculated with (2)

$$I_{Ax} = -\sum_{i=1}^{m} log_b P_i = -\sum_{i=1}^{m} I_{FRi}$$

$$I_{FRi} = -log_2(0.950) = 7.40 \cdot 10^{-2}$$

$$I_{Ax} = -5 \cdot 7.40 \cdot 10^{-2} = 0.370$$

where the outcome is given in bits. If the same system is coupled, unorganised information can be calculated by completing (5)

$$I_{UnOrg} = -\sum_{j=1}^{n} log_b\, P_j = -log_2 \prod_{j=1}^{n} P_{5FRs(t\&e)}$$

$$P_{5FRs(t\&e)} = \frac{1}{n!} = \frac{1}{5!} = 0.833 \cdot 10^{-2}$$

$$I_{UnOrg} = -log_2(0.833 \cdot 10^{-2}) = 6.91$$

and unorganised information is again in bits and may be compared to the axiomatic information of the first calculation. In this situation, axiomatic information cannot be calculated because in an unorganised design it is unclear which DPs are used to satisfy the FRs.

This case with 5 FRs already shows the unorganised information to be significantly larger than the unorganised information (0.370 vs. 6.91). This ratio seems typical in the comparison of axiomatic and axiomatic information. The ratio will precipitately increase with the number of FRs. Analogue to information, the same can be concluded for complexity; imaginary complexity is by nature of a larger scale than real complexity.

3 THE COMPONENTS OF INFORMATION

3.1 Doing the Right Things Right

A recommended way, to address design problems, was described by [Suh, 1990:67] and addresses axiom 1 first and subsequently axiom 2. In the broader domain of information, as entropy of the design, this means that unorganised information should be addressed first followed by the reduction of axiomatic information. It is not advised, as a common procedure for concurrent engineering, to address the two kinds of information simultaneously. This is because the efforts of addressing unorganised information has a fundamental effect on the design; it selects the design relations and, by doing so, it sets challenges for successful optimisation of system ranges and design ranges later on in the design process. These optimisations might be lost if the design relations are changed in a later stadium which leads to a loss of efforts. Therefore it is important that the design relations are well chosen, selecting an independent way to address FRs and preferably envisioning on the optimisation of the design ranges. This is referred to by 'doing the right things'; focussing on the right relations for the design. After this, matching the system- and the design ranges optimises the relations. This is referred to as 'doing things right'. When the two processes have competed, the system will comprise the right design relations with the right probability density functions.

From this perspective the more general concept arises that unorganised information is about doing the right things and axiomatic information is about doing things right (though these statements are not meant to be inexhaustible, they well contribute to general understanding).

3.2 RELEVANCY OF INFORMATION TO THE SYSTEM DESIGN

So far, a lack of understanding of the system design was considered to be the source of unorganised information; missing knowledge hinders the designer to make the right choices for the essential relations in the design and FRs are not satisfied by DPs. But what if a designer believes that a DP indeed does relate to an FR while in reality this is not the case. This situation again comes forth from a lack of understanding of the design; the designer does not have the knowledge that the parameter is not relevant. So what will be the effect on the information content of the design by this otiose DP? Earlier was put that the level of a design never exceeds the knowledge of the designer. However, in some cases it is possible that unorganised information is eliminated from the design and becomes superfluous. If otiose information is present in a design it could disappear. Since many system designs are redundant in some way, there is typically more than a single DP that can be optimised to meet a certain FR. According to good AD practice, the designer will decide to use the process of fixing some of the DPs [El-Haik, 2005:69]. The variable will be converted to a constant by defining its value and maintaining this situation as steady as possible. The process of fixing is continued until the design matrix is square with an equal number of DPs and FRs. The process of fixing may lead to two possible occurrences; 1) the otiose DP was maintained in the square matrix or, 2) the otiose DP was fixed.

Ad1) if an otiose DP is maintained in a non-redundant design matrix, it means that at least one of the FRs cannot be satisfied. The design matrix is not understood which leads to an increase of unorganised information;

Ad2) if the process of fixing eliminates an otiose DP from a non-redundant design matrix, all FRs can be satisfied. The DP will not influence the functionality of the system, but due to its redundancy it will increase the cost of the system. There is no impact on complexity since the uncertainty of achieving the FRs is not affected. This analysis indicates that otiose DPs that are fixed, though caused by ignorance, do not contribute to unorganised or axiomatic information. Fixing the DP has removed it from the design matrix and the FRs are no longer affected by this DP; the otiose information has become superfluous.

3.3 INFORMATION OVERVIEW

An inventory of the different kinds of information as discussed in this paper:

- Total information; the total information content of the design (full entropy of the design);
- Useful information; the part of total information that affects the relation between FRs and DPs;
- Superfluous information; information that does not affect the relation between FRs and DPs;
- Otiose information; a specific kind of superfluous information that is believed to affect the relation between FRs and DPs but in reality it does not. Otiose information is based on ignorance and therefore might increase the unorganised information content of a design;
- Axiomatic information; useful information due to a discrepancy in design ranges and system ranges;
- Unorganised information; useful information that is not recognised as such due to ignorance of the designer.

The tree of figure 1 explains the relations between these kinds of information. Note that superfluous information and unorganised information are no information according to the definition of axiom 2. Useful, axiomatic and unorganised information do affect the relation between FRs and DPs; they all lead to complexity. Otiose information only affects this relation if an otiose DP remains in the design matrix; only then it contributes to information within the definition of AD.

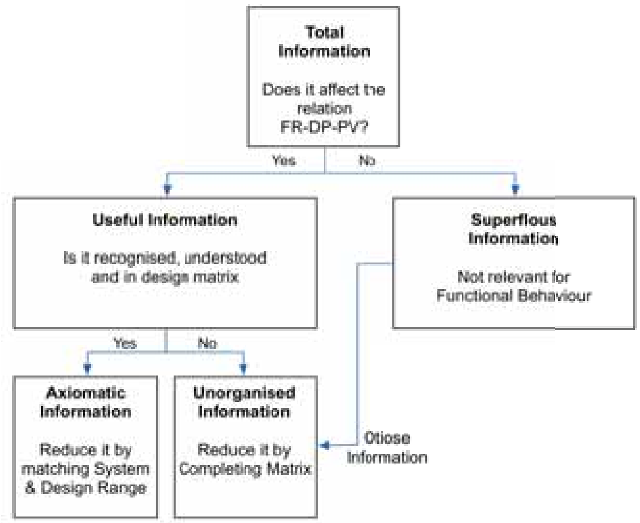

Figure 1: Overview with types of information and their relations

The kind of information can be determined by a number of two parameters: 1) is the presence of the information content recognised in the design, and 2) does it affect the FRs of the system. This is shown by figure 2.

	Relations Recognised	Relations Not Recognised
Does Affect FRs	Axiomatic Information	Unorganised Information
Does Not Affect FRs	Superfluous Information	

Figure 2: Axiomatic, unorganised and superfluous **information can be determined with two parameters**

3.4 VISUALISATION OF THE AXIOMS IN A TWO DIMENSIONAL INFORMATION SPACE

Information may be visualised in a two dimensional space. As axiomatic and unorganised information are different kinds of information, with structurally different origins making them independent of each other, their vectors will be perpendicular. According to (4), axiomatic information leads to real complexity. According to (6), unorganised information leads to imaginary complexity. Therefore this representation is analogue to Suh's complexity diagram [Suh, 2005:71].

If axiom 1, 'Maintain the independence of the functional requirements, is plotted it will guide a progressing design in the downward vertical direction as shown in figure 3. The reason for this is that axiom 1 solely addresses unorganised information: 1) the imaginary component of complexity in an uncoupled design is equal to zero which by definition eliminates the existence of unorganised information [Suh, 2005:71], 2) the process of trial-and-error does not affect the overlap of design- and system-ranges leaving unorganised information in the system untouched. This is in harmony with (4) & (6), where the outcome of (4) is constant and the outcome of (6) is decreasing.

Axiom 2, 'Minimise the information content of the design', affects by definition only axiomatic information. The component of axiomatic information is affected by matching the design range and system range but not by trial-and-error, the outcome of (4) is changes but the outcome of (6) remains constant.

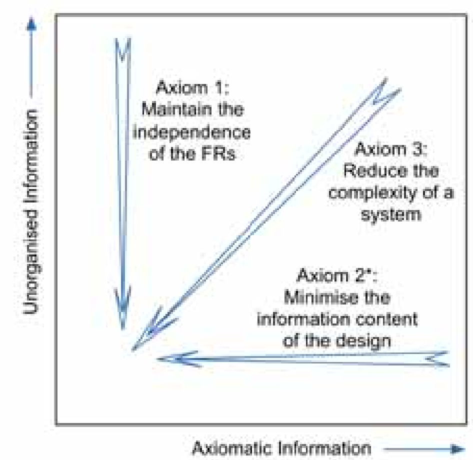

Figure 3: According to Axiom 1, a progressing design moves downward in vertical direction. **Axiomatic information is not affected**

If axiom 3 is plotted, complexity is maximal at the right upper corner and is zero in the lower left corner. Figure 3 shows the direction of a progressing design that satisfies the complexity axiom. The effect of the information axiom and the complexity axiom are in this case exactly the same; the outcome of (4) and (6) are decreasing.

4 DISCUSSION & CONCLUSIONS

A number of six kinds of information have been reviewed in this paper. Not all these kinds of information are considered to be information by the definition of information axiom.

4.1 Unorganised Information vs Complexity

Axiomatic information differs from unorganised information, which is mainly to be addressed before organisation of the design matrix. Unorganised information is very comparable to imaginary complexity though two considerations should be made before defining them as one and the same: 1) The inability of a design to satisfy the independence axiom should be considered to be information according to the definition by Shannon and Weaver and, 2) Hartley's logarithmic measure for imaginary complexity should be used as a measure. If these conditions are adopted, imaginary complexity and unorganised information are equivalent.

4.2 Axiom 1 and Axiom 2 as Corollaries of Useful Information

Useful information, as defined by Suh, is information that adversely influences satisfaction of the FRs; information content in the design will lead to a reduced satisfaction of the FRs for that design. Useful information is the aggregate of both axiomatic- and unorganised information. Therefore, it can logically be decomposed into information relating to axiom 1 and axiom 2, making the axioms fully independent. Since useful information is the basis of complexity, the same could be done with the complexity axiom. Axiom 1 & 2 are in fact corollaries of the objective to reduce the useful information content, or complexity, of a design. Though this might be considered as a disruptive determination, the operation and practical application of AD are not much affected by this for at least three reasons. First, the possibility to develop axiom 1 & 2 from the complexity axiom has already been reported by [Suh, 2005: 83]. He mentions the complexity axiom being less explicit than particularly the independence axiom and advises to apply the axioms as they are. Secondly, axiom 3 will maintain its axiomatic character in AD and will still be axiomatic in a sense that it cannot be derived from a higher truth. Third, axiom 3 is not easily applied in the design process. It does not structure the order in which the information content of the design should be addressed. Axiom 1 and axiom 2 are best maintained as starting points of the design process, and should be addressed in that particular order. This basically leaves the AD methodology intact as is.

4.3 Otiose Information

Fixing otiose DPs eliminates these DPs from the design matrix. There is no further impact on information since the fixed DP no longer affects the uncertainty of achieving the FRs. However, the designer's ignorance has not disappeared. Otiose information is always either a part of superfluous- or unorganised information.

4.4 Doing the Right Things as Game Changer

Unorganised information will equal zero for a design in which independent FR-DP relations were chosen because satisfaction of the FRs is no longer a matter of trial-and-error. A multitude of independent designs can be found for a typical design. However, depending on the chosen solution, the collection of processes that need matching of design- and system-ranges will differ per situation, greatly determining the remaining amount of work for optimisation. Therefore it is important to reduce unorganised information before axiomatic information which is referred to as 'doing the right things' before 'doing the right things'. In this statement 'things' are referring to design relations.

4.5 CONCLUSIONS

At least a number of six different kinds of information, according to the definition of Shannon and Weaver are playing a role in the design process. In the ultimate design, all information should have disappeared.

Axiomatic information, as defined within AD, has been defined considerable narrower and is limited to the matching of the design- and system-ranges of the design.

5 ACKNOWLEDGEMENTS

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