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INTEGRATING THE ANALYTIC HIERARCHY PROCESS (AHP) IN PROCESS ENGINEERING FOR INFRASTRUCTURE MODELLING AND SIMULATION (M&S)

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Abstract
Information management for collaborative Modelling and Simulation (M&S) of infrastructure includes the proper handling of information exchanges. Unfortunately, this is mostly viewed as a technological problem and much less so as a social or psychological one. To address this shortcoming, we apply multi-criteria decision analytics (MCDA) that was developed for addressing complex socio-technical choices. In doing so, we present a unique method for prioritising criteria using the Analytic Hierarchy Process (AHP) model. We have surveyed internationally a non-probabilistic sample of leading experts and stakeholders in simulation-integrated digital modelling and model data exchange. With our method, we have extended the use of the AHP model to not only evaluate alternative choices but also to set up a sorted priority order across all criteria factors. Our preliminary results show that a clear priority order can be established to reflect the preferences of all survey participants. Moreover, based on our method, it seems also possible to identify specific segments in the priority order to be addressed through process engineering techniques toward automating the outcomes. We propose that our method is especially conducive to the Design Structure Matrix (DSM) sequencing technique. The expected impact of this work is to more comprehensively extend the application areas of the AHP to process engineering throughout the requirement gathering phases of collaborative infrastructure M&S.

1.1 INTRODUCTION

With the practice of precinct scale information modelling, or PIM, it is becoming clearer that it is to aim more at emergent, and less at predefined arrangements as opposed to BIM-based modelling practices. For example, Mark Burry and colleagues describe behaviour templates, e.g., for the growing and decaying habit of tree species [1]. On the other hand, Christopher Alexander (1964) [2] and others have given many examples for constructing flexible and adaptable pattern languages, sometimes called shape grammars. In PIM, therefore, we are concerned with defining object behaviour under some transformation. Thus, one is concerned with the shaping of objects but also with the transformation and manipulation of relations. Hence a process map is also shifting in focus as well as gaining new functions. Each process element thus also becomes a container or module into which some influence may map into, internal or external.

Specifically for Modelling and Simulation (M&S), analytical techniques such as Analytic Hierarchy Process (AHP) or other multi-criteria decision analytics (MCDA) tools can have the highest impact on the lifecycle of the process when applied early [3]. The interest of this research is in applying such techniques to collaborative exchanges in precinct energy infrastructure information modelling. Typically, and as a legacy of BIM-based modelling, this starts directly with the process modelling stage. However, those requirements are too elaborate to allow such flexibility that would be welcome in the conceptual phase when uncertainty and intangible criteria prevail in making decisions. At this stage, pools and lanes for a process model are also difficult to separate in order to distinguish such actor roles that may need to be defined in due course. Pools and lanes might also need more flexibility in the final modelling since their separation can be confusing, even conflicting [4].

We have developed the first principles of a method to make the development between conceptual and elaborate process mapping more continuous by also integrating MCDA techniques. The approach was elaborated through and tested on the results of empirical observation from surveying international experts in a small non-probabilistic sample population.

The rest of this paper is structured as follows. Section 1.2 first introduces AHP hierarchies as intent structures and precedence networks as they may be defined through interpretive structural modelling, before briefly discussing the problem of priority reversal in ranking decision criteria. Section 1.3 outlines the methodology of encapsulating rank reversals in partitioned modules of priority feedback blocks. It introduces observed patterns for sets of three and applies similar partitioning principles to a hypothetical non-trivial reversal pattern in sets of four. Section 1.4 shows how patterns identified are applicable to rank reversals observed on our survey data. Conclusive discussions are reported in section 1.5.

1.2 BACKGROUND

1.2.1 Criteria ranking

Analytical Hierarchy Process (AHP) method [5] is one of many MCDA techniques [6]. It was developed to take into account cognitive limitations of short term memory and typical psychological shortcuts in making decisions resulting in inconsistent judgments when comparing things. It was devised to invite and take advantage of such inconsistencies in making better decisions and being able to argue about them in a more formal way.

Though the method is pen-and-paper friendly, it may also be assisted computationally when too many factors are at play. The method's further strength lay not just in evaluating a complex system of factors but also in structuring them for data input and analysis. The analysis is carried out on the outcome of pairwise decision factors made by those who are stakeholders in the complex issue or phenomenon at hand. The method was initially designed to evaluate and support complex decision choices made between alternative options. The field of application has much expanded since, including evaluation of factors toward developing a process model [7] and prioritising process variants [8]. The problem with AHP is often in the treatment of rank reversals in a priority order. It can happen, for example, due to the inconsistency in the initial decisions, or as a result of introducing new factors in subsequent decisions.

1.2.2 Precedence networks

For making pairwise comparisons that may be computationally enhanced, Interpretive Structural Modelling (ISM) is another method used for structuring and evaluating complex matters [8,9]. It may be used in combination with AHP, for example, to build the hierarchical structure of interacting factors according to some specific relationship between them. Applying ISM generally results in strictly transitive orders, but this may not always be the case. For example, the relationship 'north of' used in ordering cities geographically [10] does not exclude the possibility of two places located at exactly the same latitude. And in terms of rank reversal, what precedes what in a precedence network [11] may flip when a new process element is introduced. An assumed sequence for nested processes may also flip when they can only be evaluated for such relationships in subsequent sessions. More generally, a precedence network can be formed early on in the process, or in a conceptual phase, when durations may not be known. By contrast, most other techniques, like those used for task scheduling in project management, also require other inputs, such as activity durations.

1.2.3 Rank reversal between the priorities of multiple criteria

Rank reversal can be an important issue in MCDA such as AHP when mitigation of its effect is sought. It happens when the same order of importance that was factored into decisions changes. For example, when the priorities assigned to decision criteria reverse their order of importance. One way to mitigate its effect is to feed back the weighting vector for the criteria set calculated from one series of decisions into a follow-up session [12]. For effective mitigation, it is known to be much easier to trace the reversals when criteria are broken down into smaller sets [13].

Priority feedback has also been described for real-time processing as feedback to some time series based on different requirements. In both of those instances, the feedback is time-dependent or temporal. We describe a model for conceptually non-temporal priority feedback that is extensible toward more continuous process engineering between requirement discovery and process modelling.

1.3 METHODOLOGY

To mitigate the effect of traceable rank reversals of priority criteria, we describe conceptually non-temporal priority feedback to characterise experimentally induced reversals observed on small sets reordered in pairs. The model has been tested to be recursively applicable to sets with up to five elements. To do so, we apply to the ranking orders such descriptive differentiation that directly relates interacting actor roles when modelling the process with potential pools and lanes for the target M&S use case.

1.3.1 Reversal pattern encapsulated

There are only so many reversal patterns possible for small sets. We have catalogued these for sets of three but observed only some of them occurring prominently and persistently among pairwise reordered sets. For these, we devised a method to arrest the effect of rank reversals. We represented the orders with weighted directed graphs, then superimposed them, and partitioned their matrix form. We applied such partitioning that allows some bidirectional link between the modules also modelled as feedback between sub-matrices on the main diagonal. We show one such pattern on the specific example that follows.

1.3.1.1 Intent priorities mapped as precedence

First, we show the effect of priority reordering on an example precedence network onto which it maps as depicted in Figure 1. For intents B, C, and D structured as siblings under a parent intent in a hierarchy there are three potential priorities, High, Middle, and Low. We show two potential priority orders a.) and b.), and the related precedence networks, where there is a single transitive relationship to order tasks assigned to each intent. This relationship reads as 'preceded by'.

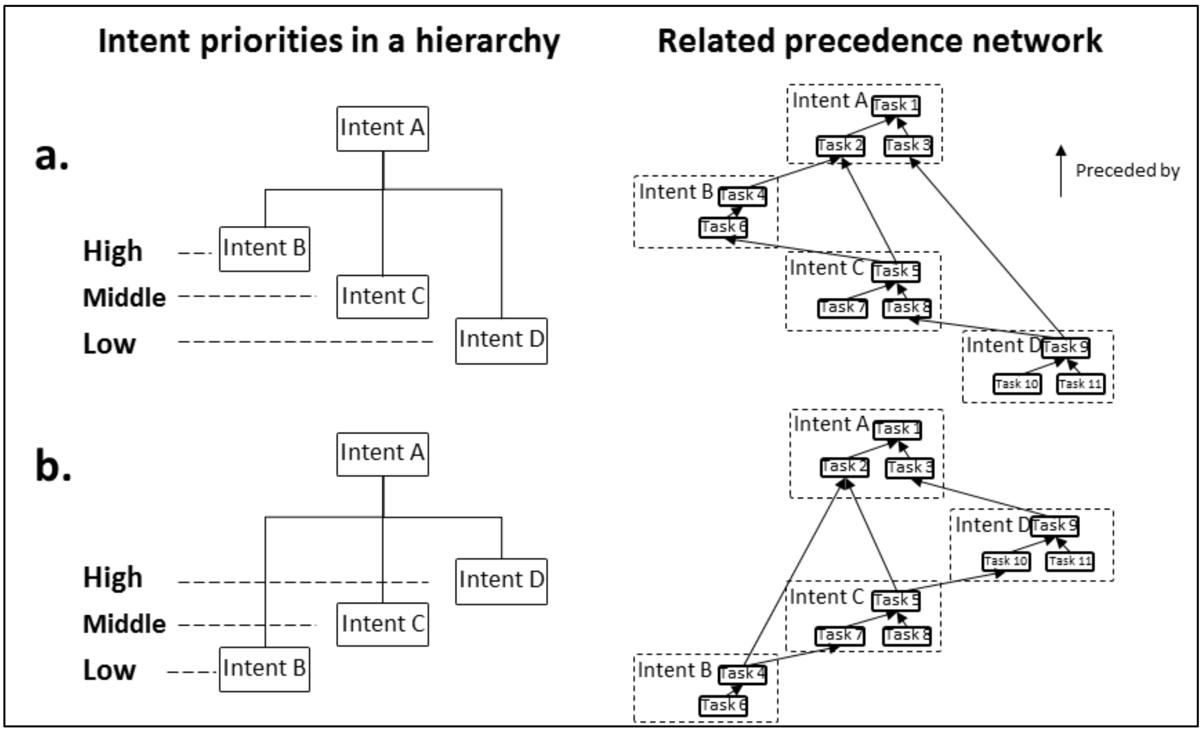

Figure 1. Intent priority reordering mapped to a related precedence network.

We now focus on just the sibling intents in order to more closely observe the effect of the priority reordering on the related precedence networks as shown in Figure 2. Tasks entailed by a higher priority intent are ordered as preceding the others. Priority difference is shown with thick lines with arrows pointing in the direction of the lower priority. We also mark the largest priority difference with a thick dotted line.

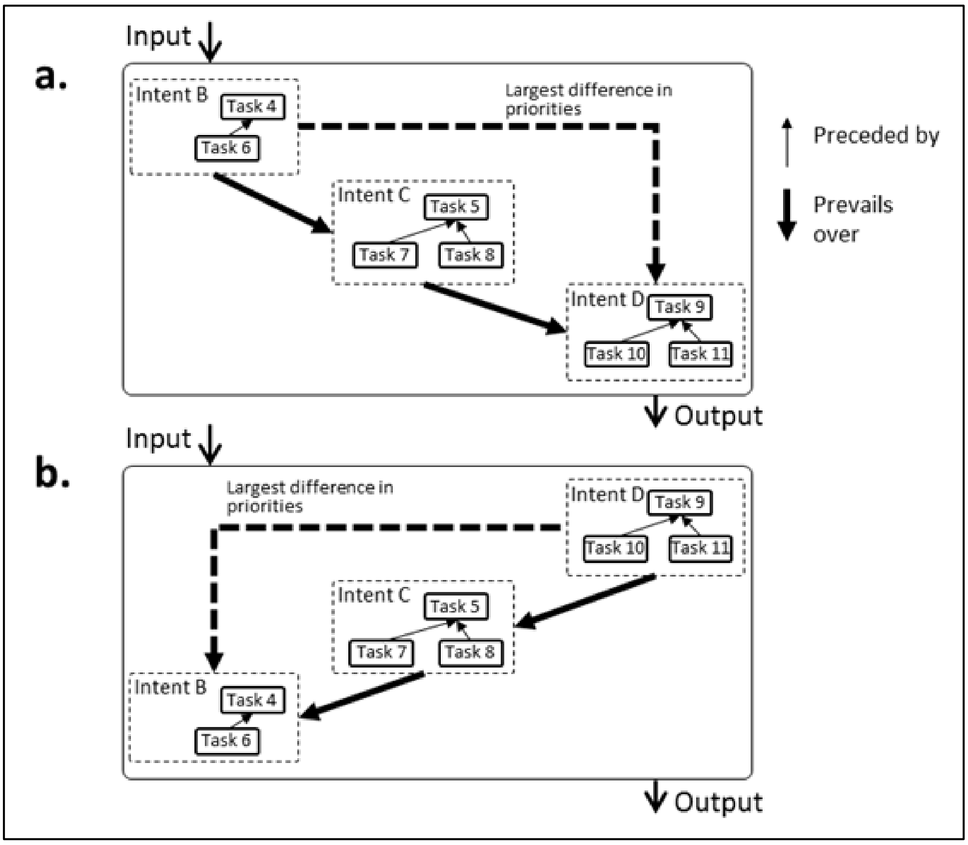

Figure 2. The effect of priority reordering on the precedence of tasks.

Intent orders are now transferred to two directed graphs superimposed over each other. For the superimposition, we take b.) as the reference order, meaning the transitivity structure used as a control to which the other order a.) is being compared.

In Figure 3 we depict the result, by also showing two potential ways of partitioning the related matrix and the one indicating a better modular option, which is also depicted as a priority feedback block. We have assigned multiplicity to the directed edges of the graph such numbers that represent both the importance and the status of the priority difference between nodes, where arrows point in the direction of the lower priority. Fraction marks the highest priority difference in the reference order, and a zero marks the same in the referent order. The partitioning prefers the fraction to fall outside the submatrices along the main diagonal. It also allows minimal feedback between the submatrices, where feedback is depicted with X, but stipulates that either the highest aggregate multiplicity count should be within the sub-matrices, or the portioning should fall closer to the output. This is to mark criticality with the placement of the partition, and also for further processing with DSM, in which it is held that inputs are always easier to capture than outputs.

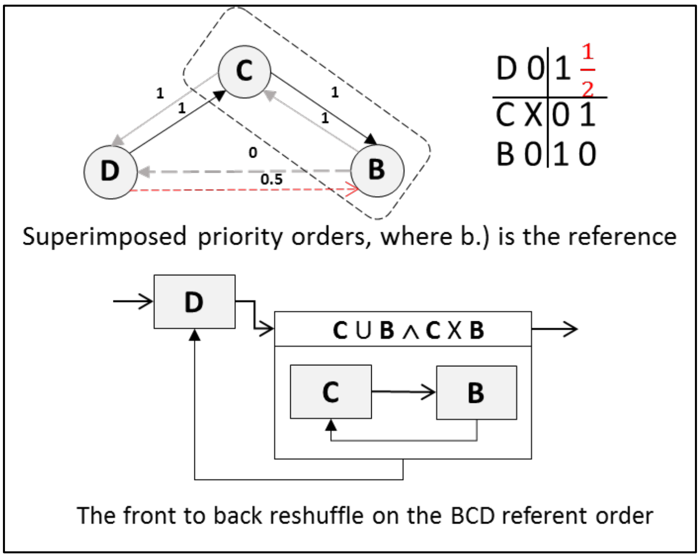

Figure 3. Example partitioning of a two superimposed priority orders for sets of three.

The example depicts the way of arresting the effect of the same rank reversal, as is shown in Figure 2. It also shows the potential logic for producing the label for the partitioned priority module by way the set operators Union or Cartesian product, for example, on the key content of the verb models that can map intents to tasks [14]. Admittedly, it is more interesting to apply the same concept to larger sets, such as for example a transitive order of three elements. The result is not trivial, although rules for sets of three do apply recursively. We show this in Figure 4 on the example of the front triad reshuffle in place which also includes the front pair reshuffle to back pattern for the front set of three. For more clarity, we colour code the node with the highest priority in light green and the lowest priority in light red.

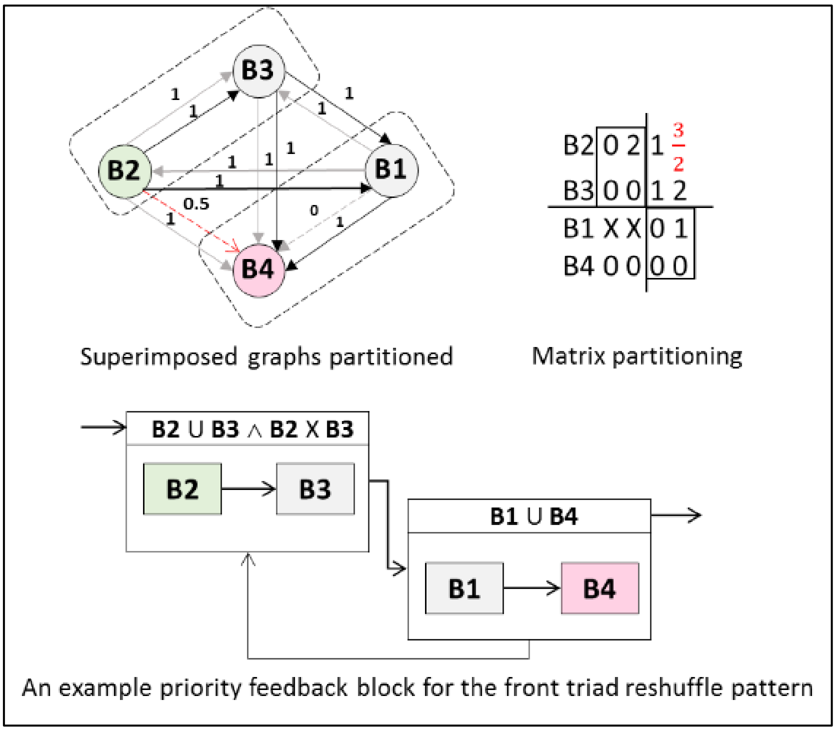

Figure 4. Example partitioning of a priority feedback for sets of four.

1.4 APPLICABILITY TO CRITERIA PRIORITY

We have provided the results of two priority orders compared pairwise, where the criteria have been mapped to the tasks they entail in Table 1. Each was created with a scalar multiplier on the weighted priority vectors using the expert ranking index. Both the initial transitivity order and the order containing the reversed ranking is shown, where the criterion that was compared by experts is marked with an X. A mark in a shaded field indicates a specific reversal when compared to the reference order which was differentiated using the descriptive parameters of the overall expertise of experts. We show the related two priority rankings side by side, which is the result of the reference order induced using the overall expertise of stakeholder experts in the ranking index, and Systems Engineering as a specific expertise among them, for the referent order.

Table 1. Matrix showing the reversal of criteria ranking.

		A			C			B			F			E			3D modelling	Systems Eng.	Energy Simul.	BIM Modell.	Specific expertise factored in: Systems Engineering	
		A2	A1	A3	C3	C2	C1	B1	B3	B2	F1	F2	F3	E1	E3	E2					Weighted priorities*	Priority rank
A	A2		x	x																	23.046	3
	A1	x		x		X			X								x	x			24.653	1
	A3																				3.496	14
C	C3					x	x														24.350	2
	C2						x		X				Unbroken transitivit						x		13.905	5
	C1																				7.739	9
B	B1								x	x											3.991	13
	B3							x		x											4.015	12
	B2							x													6.546	10
F	F1											x	x								21.052	4
	F2			Order reversal									x		X		x	x			8.214	7
	F3																				3.331	15
E	E1														x	x					9.946	6
	E3															x					8.016	8
	E2																				5.192	11
3D Modelling			x									x						x		x		
Systems Eng.			x									x					x			x		
Energy Simul.						x											x			x		
BIM Modelling																	x	x	x			

*Globalised AHP priority vector values multiplied by the expert ranking index

Modelling the AHP results this way allows the direct comparison of the criteria and their reversal with the descriptive data collected on expert's primary interaction when engaging in a scenario like the use case that was presented to them. As can be seen, the two rank reversals are front pair reshuffle in place for A1 and A2, and back pair reshuffle to front for B3 and B2, where each can be arrested the respective modules of the corresponding priority feedback blocks. Moreover, rendering the results in a multi-domain matrix Li and Tate [15] can also reveal the relationship between the interaction of actors and which expertise, skill, capability, etc., associates with the highest priority for a certain parent criterion. This can give a more concise way when beginning to form pools and lanes for interacting roles in an ensuing process model for the tasks.

1.5 CONCLUSIONS

In response to the more flexible needs of precinct scale information modelling exchange, we have described and tested a conceptually non-temporal priority feedback model that is extensible toward more continuous process engineering between requirement discovery and process modelling to mitigate known effects of traceable priority criteria ranking reversals. It was inferred from experimentally induced reversals observed on pairwise ordered sets of three elements.

Although yet larger sets may be attempted recursively, it may not be plausible beyond sets of three or four, due to cognitive limits imposed by our short-term memory, and because data is known to be collected under such limitations [16].

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