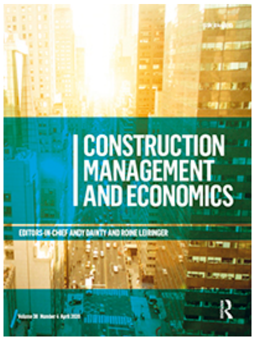

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Design science research in construction management: multi-disciplinary collaboration on the SightPlan system

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ABSTRACT

As a tribute to Ray Levitt's early computer science contributions, this paper presents the research methodology he and I in close collaboration with Barbara Hayes-Roth followed to develop the SightPlan system. This research methodology falls under the umbrella of what is known as "design science." Design science concerns itself with designing and making artefacts to fulfil a purpose, and then testing and validating that they indeed are fit-for-purpose. Design science does not belong in the category of physical science or of fundamental science; instead, it falls in the category of the sciences of the artificial. This paper describes the methodological steps pursued in design science and in parallel illustrates how these steps were instantiated and what artefacts were produced in the course of developing the SightPlan system, a blackboard expert system that lays out temporary facilities on construction sites. The aims of this paper are to recognise Ray's work as an advisor and researcher, reflect on and promote the use of design science in construction management and economics and thereby participate in the ongoing discussion on research methods in this journal, and illustrate to scholars in this field that research is an opportunistic endeavour.

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Design science; artificial intelligence; expert system; knowledge management; site layout; planning; constraint satisfaction

Introduction

This paper offers a contribution to the Festschrift in Construction Management and Economics (CME) prepared in honour of Professor Raymond E. Levitt at the time of his retirement from teaching at Stanford University in 2019. Early in his career at Stanford, Ray recruited me to become a PhD student. One of his early students and his first female PhD student—with, I am pleased to say, many more students and especially female students to follow as his advisees—I am much indebted to him for encouraging me to pursue a scholarly career path and for shaping my ability to succeed along the way. Ray was exceptionally generous and nurturing in offering advice and food for thought, from which I hugely benefited especially in my formative years, the years I studied at Stanford (1984–1989).

As a tribute to Ray's early computer science contributions, this paper presents the research methodology he and I pursued in close collaboration with Dr. Barbara Hayes-Roth more than 30 years ago. Together, we developed the SightPlan system, a blackboard expert system that models and augments human decision-making for designing construction site layouts (Tommelein 1989, Tommelein *et al.* 1987a, 1987b, 1990, 1991, 1992a, 1992b, 1992c).

This research methodology is known as "design science." Design science (e.g. March and Smith 1995, Hevner *et al.* 2004, Gregor and Hevner 2013, Vaishnavi *et al.* 2004/2019) concerns itself with designing and making artefacts to fulfil a purpose, testing and validating that those artefacts indeed serve the intended purpose and do not have unintended consequences, and then improving them as needed. Design science does not belong in the category of physical science (such as physics or biology, i.e. the study of things that exist in and of their own in the world) or of fundamental science (e.g. mathematics). Instead, it falls in the category of the "sciences of the artificial" (Simon 1969). While I don't recall explicitly using the term at the time, literature fundamental and related to design science were certainly on my PhD student reading list (including Kuhn 1962, Simon 1969, Newell and Simon 1972, Hofstadter 1979, Dreyfus and Dreyfus 1986). The methodology we followed resonated with my understanding of what was expected for good engineering research (I was a Master's and PhD student in the Construction Engineering and Management

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Programme in the Department of Civil Engineering) and what was expected for good knowledge engineering research (I also studied Artificial Intelligence as a Master's student in the Computer Science Department's Knowledge Systems Laboratory (KSL), a laboratory where pioneering work was done on knowledge-based expert systems).

The aims of this paper are to recognise Ray's work as an advisor and researcher, to reflect on and promote the use of design science in CME and thereby to participate in our community's discussion on research methods, and also to offer an illustration to scholars in this field that the pursuit of research is an opportunistic endeavour. Indeed, "[s]cience is not a smooth, authoritative progression, but lurches forward in a series of semi-rational fits" (Economist 1996).

This paper is structured as follows. The next section lends support to the assertion that the study of CME can benefit from pursuing multi-disciplinary design science. It is followed by a short section describing the SightPlan system, so that the reader will be able to subsequently recognise the system's architecture and design features when they are highlighted in the analysis that is provided. The analysis takes two tacks on the characterisation of the research steps taken and artefacts produced. First, it describes SightPlan according to the five dimensions for knowledge generation proposed by Voordijk (2009). Second, it describes SightPlan according to the design science framework proposed by March and Smith (1995) and expanded on by Hevner *et al.* (2004). This characterisation then lends itself to reflect on research methodologies used in CME. The summary and conclusion section recaps the contributions to knowledge we made in our collaboration on SightPlan, and it also allows me to express my gratitude to Ray.

Construction management and economics (CME): a multidisciplinary design science

This paper builds on Voordijk's (2009) assertion that "Research in the field of construction management and economics (CME) can be characterised as a multidisciplinary design science. Results from the sciences and humanities are necessary inputs for this field of research that deals with design, production and operation of the built environment." This assertion can be augmented by stating, likewise, that results from CME research can offer necessary inputs to other fields of research.

The conception and development of the SightPlan system indeed leveraged knowledge and expertise in two domains: the domain of construction management (Ray's strength) and the domain of cognitive science (Barbara's strength). Each of these, in and of their own, are very broad. Construction management needs no further definition in this journal. However, what is meant by cognitive science warrants clarification especially in light of the ongoing discussion on the role of social sciences in regard to research in CME (e.g. Betts and Lansley 1993, Seymour *et al.* 1997, Raftery *et al.* 1997, Runeson 1997, Rooke *et al.* 1997, Chau *et al.* 1998, Voordijk 2009, Volker 2019), a topic revisited later in this paper. "Cognitive science is the interdisciplinary study of mind and intelligence, embracing philosophy, psychology, artificial intelligence, neuroscience, linguistics, and anthropology. Its intellectual origins are in the mid-1950s when researchers in several fields began to develop theories of mind based on complex representations and computational procedures" (Stanford 2018). As such, cognitive science is highly relevant to the domain of CME. This combination and leveraging of two domains of expertise offered a rich setting for model development, experimentation, learning, and generation of new knowledge.

SightPlan: blackboard expert system to plan and lay out construction sites

An overview of the SightPlan system is presented next, in order to help readers understand the system's architecture and design features. It is a very brief overview. Tommelein (1989) and Tommelein *et al.* (1987a, 1987b, 1990, 1991, 1992a, 1992b, 1992c) offer much more detail.

Our research focussed on temporary facilities such as laydown yards, trailers, and stationary equipment, that are positioned on- and removed from site during the construction of a project. Determining their location on site is a spatio-temporal arrangement problem: the construction site layout task is to position objects in space and over time subject to arrangement constraints in a certain context. SightPlan was to be programmed as a rule-based system (with rules capturing human expertise and heuristics) to assist project managers with laying out temporary facilities on construction sites, by guiding them through layout planning process and helping them visualise the result (i.e. the "sight" in the system's name was not a typo!).

I implemented the SightPlan system using the BB1 blackboard architecture (Hayes-Roth and Hayes-Roth 1979, Hayes-Roth 1985). This software architecture emulates a classroom setting, where participants—

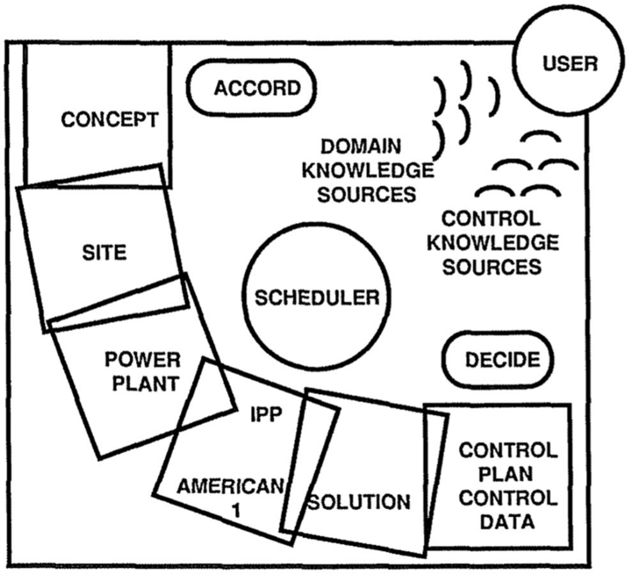

Figure 1. Blackboard metaphor (Figure 4.2 in Tommelein 1989).

called knowledge sources (KSs)—see a problem described on the blackboard (BB). Figure 1 (Figure 4.2 in Tommelein 1989) illustrates the blackboard metaphor as it applied to the SightPlan system. Presumably, no KS can solve the problem on its own, but each one may be able to contribute one or several problem-solving steps that, when combined in a reasonable sequence, may lead to a solution.

KSs are of two kinds. A SightPlan Control KS will identify what strategic actions to add to- or how to modify the strategy that is posted on the CONTROL PLAN/CONTROL DATA board (words in caps refer to boards that are shown in Figure 1), i.e. they are to plan what to do next or sometime in the future. In contrast, a SightPlan Domain KS will identify an object to position and apply the constraints it has with other objects already in the layout posted on the SOLUTION board, i.e. they are to do what needs doing. Once it finds one or several suitable positions for it, it will accordingly update the SOLUTION board.

By assessing all data posted on the boards each simulation cycle, KSs know when to focus their attention and when to propose making a change on a board. At each cycle, the so-called SCHEDULER considers the contributions that KSs propose and selects the best one, based on the strategy being followed, which then gets to make a change. The cycle then repeats. Thus the inference mechanism of BB1 (embodied by the SCHEDULER) is both incremental and opportunistic, and the architecture promotes a kind of collaborative problem solving (KSs cannot directly communicate with one another; they share data posted on the boards). Generally speaking, the strategy followed is that of arrangement assembly with constraint satisfaction: picking one object at the time and adding it to the layout while meeting the constraints imposed on it.

The actual computation to determine the coordinates of positions of objects in the layout is done by making a call to the GS2D constraint engine (Confrey and Daube 1988). By design choice, GS2D works on rectangles represented in two-dimensional (2D) continuous space, and oriented at 0 or 90 degrees. GS2D takes as input sets of possible locations of two rectangles and a constraint to be met between them, and it reduces those sets to include only those locations where the rectangles meet the imposed constraint. Only impossible positions are excluded. This feature (GS2D keeping track of infinitely many possible positions of a rectangle, succinctly described by means of sets) offered computational support far superior to what any person could keep track of in their head. It enabled us to experiment with postponed-commitment strategies, as opposed to the early-commitment strategies people have to use due to cognitive limitations (Tommelein *et al.* 1992a). I also programmed a temporal strategy for SightPlan, extending the representation and reasoning to include the presence of objects on site for a delimited time interval. The layout solution was then a sequence of layouts over discrete time intervals and could be animated.

Blackboard data is structured hierarchically and layered in modules to allow for reuse and analogical reasoning. For example, arrangement assembly problems occur in many domains. Figure 1 illustrates the domain can be specific (the board "IPP and AMERICAN 1" refers to data specific to the two cases I studied), or more general (e.g. as shown on other boards, these cases pertained to POWER PLANTs, power plant sites are a kind of SITE, and sites can be represented with even more abstract CONCEPTs).

While the SightPlan-specifics layered over the BB1 architecture enabled us to model a strategy and use constraint satisfaction to compute a layout solution, we needed a 2D graphical display of those solutions to help us in the process of debugging the programme and assessing the results. The black-and-white bitmap display I developed (Figures 2 and 3) proved to be very useful not only to me but also when I was explaining the system to people not familiar with BB1 or rule-based systems. The person involved in validating SightPlan's process and solution viewed it and assessed the quality of what he saw using expressions such as "This arrangement does not look quite right" and "That looks good." This conversation would have been nearly impossible without 2D visualisation.

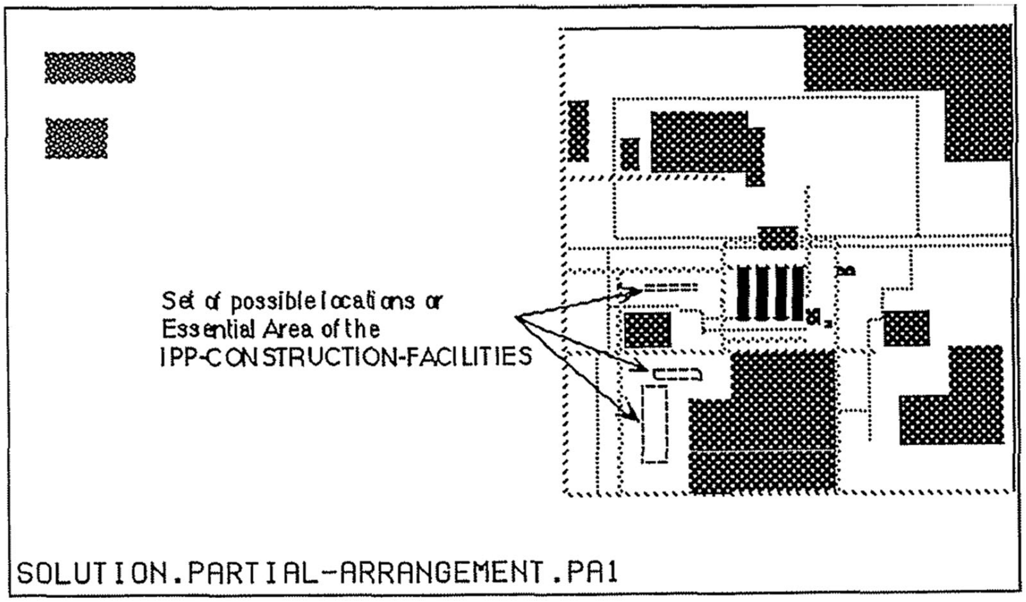

Figure 2. SightPlan's black-and-white bitmap display. Dashed rectangles indicate sets of positions for the centre point of a rectangle being positioned, computed by GS2D (Figure 6.17 in Tommelein 1989).

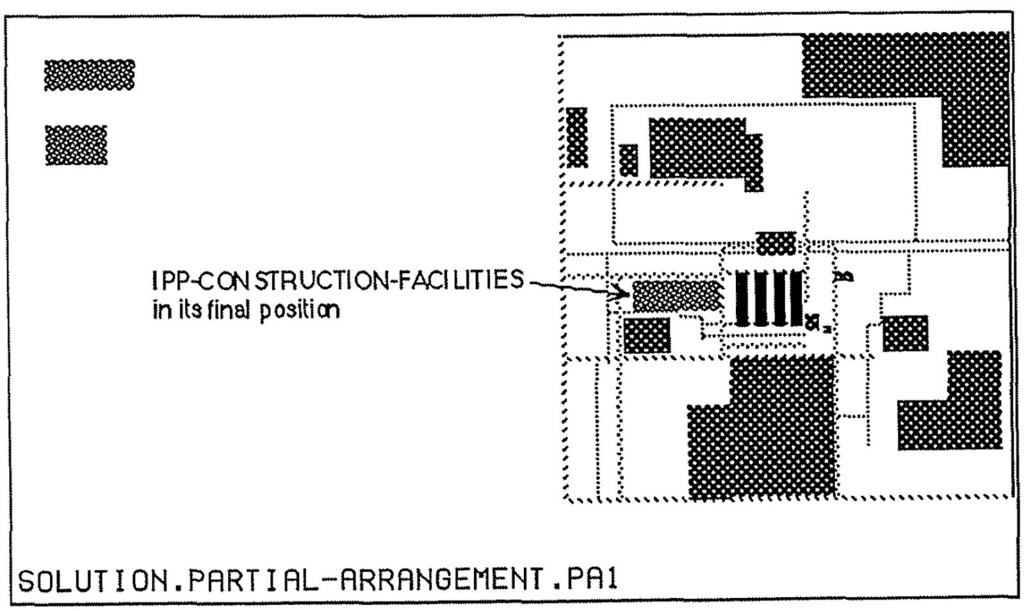

Figure 3. SightPlan's black-and-white bitmap display. Grey rectangle shows the rectangle in its final position computed by GS2D (Figure 6.18 in Tommelein 1989).

Furthermore, Tony Confrey developed an interactive graphical display in colour, named SightView. Using SightView a user could interact with SightPlan in real-time in two ways (i.e. act like a KS, but one that is external to the blackboard system): (1) use the interactive graphics to select one out of a set of possible positions and (2) override the BB1 scheduler decisions (Figure 4). We did not study user interaction with the system and its impact on problem solving, but suggested it as a promising area for further research.

SightPlan's architecture and design features, just outlined, will be used next to illustrate the steps taken in design science.

Five dimensions of knowledge-generating (epistemological) activities

The development and characteristics of the SightPlan system help illustrate the five dimensions Voordijk (2009) proposed for knowledge-generating (epistemological) activities. After this is done, the research

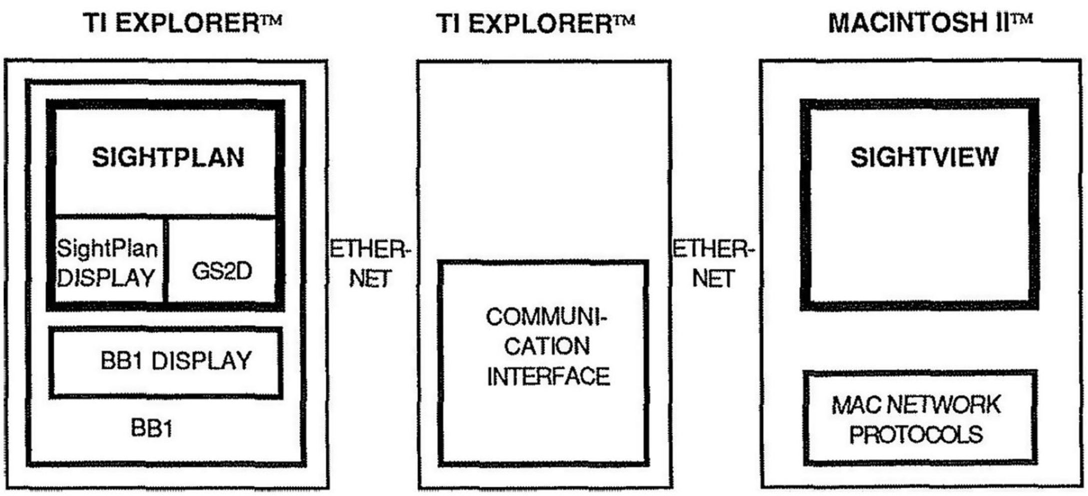

Figure 4. SightPlan-SightView communication interface (Figure 4.29 in Tommelein 1989).

activities and outputs from SightPlan will be situated in a design science framework. Voordijk's dimensions are expanded on in the following order: (1) the objective of the epistemological activities, (2) the methodology, (3) the objects of knowledge, (4) the characteristics of the results, and (5) the quality criteria.

Activity 1: define the objective of the epistemological activities

The mission [goal] of a design science is to develop knowledge that the professionals of the discipline in question can use to design solutions for their field problems (Van Aken 2004). This is the goal Ray challenged me with when launching our research: to "solve" the construction site layout problem or, at least, design a means to "address" the site layout task.

The distinction between solve and address is epistemologically important. Engineers are trained to make assumptions about the world, introduce abstractions, and draw boundaries around their problem so that it will be isolated from its context and then can be solved more-or-less optimally. Having found a solution, they then have to figure out how to apply the optimal solution to the real world and, quite often, encounter challenges in doing so. In contrast, other people in the real world (such as construction managers and other practitioners in the built environment) have to address practical tasks and concerns possibly in less optimal- yet presumably still satisfactory ways. They must address tasks and concerns with countermeasures, i.e. not necessarily call the problem solved, because of the full realisation that the resources available to make decisions are bounded and, furthermore, new situations will arise in ever-changing contexts, so that follow-on tasks and new concerns will emerge, in turn demanding to be addressed. In practice, decision makers may be informed both ways, using a combination of problem solving and application of countermeasures, as means to sharpen their intuition on potential alternatives while also meeting the demands imposed on their judgment. (Although the overview on SightPlan mentioned problem solving, it would have been more appropriate at the time and now to say that the system addresses the layout task).

In Spring 1985, Ray had just returned to teaching at Stanford from a sabbatical at Intellicorp, a Palo Alto, California based software company involved in developing knowledge-based expert systems (KBES) programmed in LISP. The development of KBES falls into the paradigm of Artificial Intelligence (AI) that is related to human cognition (e.g. Lenat and Davis 1982, Waterman 1986). Ray was keen to explore opportunities to apply methods used to develop KBES to tackle construction management problems. The layout of temporary facilities on construction sites stood out as being a problem that is hard to solve (e.g. Garey and Johnson 1979). It required consideration of a variety of knowledge (including factual data and rules-of-thumb describing constraints) and spatio-temporal reasoning. Practitioners appeared to use some kind of trial-and-error to create a layout. There appeared to be no method to solve the problem using mathematical optimisation. Moreover, few construction management books at the time ever mentioned space as a resource to manage (such books commonly mention five resources: (1) materials, (2) manpower, and (3) machines, as well as (4) time and (5) money), so how then was it managed?

With the research rationale and topic defined (e.g. Javernick-Will 2018), the epistemological activities pertaining to our SightPlan research started with defining objectives. As is commonly the case, their specifics became more clear only later on, in the course of conducting the research:

1. Explore AI architectures (including different types of rule-based systems) for addressing the class of spatial arrangement problems to which site layout belongs.
2. Design a method to lay out temporary facilities on a construction site by applying a KBES approach to this "hard" construction management task. Note that we aimed to examine the approach of using carefully-selected domain knowledge and a flexible reasoning mechanism to gain advantage over generic and more rigid heuristic construction methods. It was not our ambition to develop a narrow and deep expert system that could match and possibly exceed the performance of a human expert in site layout.
3. Capture knowledge related to the layout of temporary facilities on construction sites that is brought to bear to address the layout task. This knowledge initially came from the literature, though that literature was very limited. My research augmented this knowledge base by adding rule-based heuristics acquired through interviews with one-site field personnel and other construction practitioners.
4. Develop new and generalisable knowledge, sufficient to meet the requirements of research worthy of a PhD degree:
5. Study alternative strategies for layout planning. Lacking knowledge of mathematical approaches to solve this problem in an optimal way, the SightPlan artefact became the laboratory to explore satisfactory outcomes. We chose arrangement assembly as the method to step-wise construct the layout by positioning one object at a time.
6. Use the BB1 blackboard system architecture and apply it in a new domain. Up until then, Barbara and her team had been using BB1 to develop PROTEAN, a computer programme that interprets spectroscopy data of proteins in solution and uses approximate analysis as the strategy to obtain protein structural information (Duncan *et al.* 1986, Hayes-Roth *et al.* 1986a). PROTEAN's task was 3D arrangement assembly informed by incomplete data. SightPlan presented another domain of application to test the generality of BB1's architecture. Its task was 2D arrangement assembly informed by rule-based heuristics that captured human expertise. Subsequently, Barbara explored the domain of real-time control of patients in an intensive care unit (Hayes-Roth *et al.* 1992) and then moved on to studying real-time adaptive control (Hayes-Roth 1995).
7. Programme a generic 2D arrangement assembly language (Confrey and Daube 1988) and graphical user interface to compute and display feasible site layouts.

Activity 2: define the methodology

The research process tends to be depicted, at times, as the pursuit of a chosen methodology in a step-wise fashion. Although a researcher will follow her path step-by-step, in retrospect looking at the path followed, it is notably not at all linear but rather erratic and dotted with junction points where opportunities presented themselves and choices had to be made based on the researcher's bounded rationality (Simon 1969). Furthermore, research paths have hurdles along the way, which may turn out to be stopping points and dead ends, thus requiring iteration and backtracking. Steps also overlap and often are highly intertwined with one another.

Conducting a literature review

An essential part of doing research is to review the literature, not only at a certain point in time but on an on-going basis because the frontier of knowledge is ever-advancing at an accelerating pace. Doing so is not only inspiring, it also enables the reader to determine if they can build on the work of others and possibly stand on the shoulder of giants in pursuit of their own work, while avoiding the embarrassment of thinking to have found something new, only to later discover that others found it already. My recollection is that Ray sketched the vast world of publications as illustrated in Figure 5. I have redrawn this figure many times since to explain the literature review process to my students and even colleagues, so this depiction is likely somewhat different from his. This notwithstanding, other students of Ray's will likely recognise it.

Exploration of the literature tends to progress in the following way. A student finds themselves in the midst of and surrounded by a vast body of literature [1], a body that expands at its borders as time progresses [2]. A search for reading material may be spotty (marked by an x) at first [3], but will gain focus and become more directed as the student finds topics of interest and is able to direct their search choosing

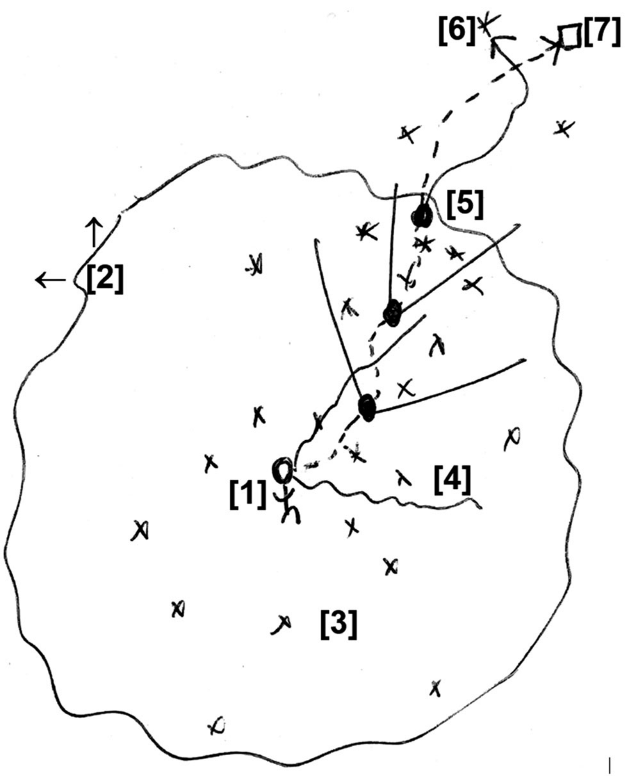

Figure 5. Moving about in the body of literature towards the knowledge frontier (after sketch by R.E. Levitt circa 1985).

one or multiple, possibly inter-related topics [4]. A structured literature review using a well-defined set of sources (e.g. selected journals or conference proceedings) and key words may offer a starting point for reading up on past work on a specific topic, but it is far from sufficient to meet the requirements of a comprehensive search.

While reading, the student will be able to create a mental image of who is who in which field and spot the relatedness of research conducted by advisors, advisees, and collaborators, develop awareness of existing schools of thought and paradigms (Kuhn 1962), learn about problems tackled and solution methods applied, as well as see numerous examples of how research results may be presented (e.g. read not only the technical peer-reviewed literature, but also trade publications, online postings, and dissertations). One way to pin down a research topic is to do a gap analysis. Figure 6 lays out the construction site layout literature up to the mid-1980s and illustrates gaps within it. The vertical axis depicts how general (at the bottom) vs. domain-specific (at the top) the described work was (each paper described a so-called instantiation, a term explained later in this paper). The horizontal axis depicts whether the described method is applied in manual- (shown on the left are guidelines, heuristics, and checklists) or computerised layout generation (shown on the right is mathematical optimisation). The cross-hatched area shows where the SightPlan research aimed to make its research contributions.

By reading more of the literature, the student should gradually progress (follow the dashed line in Figure 5) towards the boundary of knowledge as presented in publications [5], and synthesise what has been done to date in the chosen field. From there, questions arise and a research proposal may be formulated. A PhD-level proposal should aim to extend the body of knowledge in the field and accordingly the literature [6]. When the research then is carried out, aiming to get to [6]—recognising that plans are forecasts and forecasts are always wrong—the student will likely end up in a slightly different place [7] from what was anticipated, but hopefully still have made a contribution to knowledge sufficient to meet degree requirements.

Figure 5 presents the literature as one vast body. Any perceived domain boundaries are artificial (created by journal editors, authors, etc.); they should not be self-imposed when it concerns the researcher. The researcher should try to efface any apparent boundaries and look out for what can be learned from other fields (e.g. Volker 2019).

Choosing the model

As Ray was keen to explore the use of KBES and wanted us to be informed of the latest developments in the field, he had me attend the 9th International Joint Conference on Artificial Intelligence which happened to be nearby, in Los Angeles, California in 1985 (IJCAI 1985). Note that I had become aware of KBES only earlier that same year, so: all power to Ray to send me to this conference bright eyed and bushy tailed!

Insofar as I can remember, I sat next to Mark Stefik on the plane. He had been conducting research on hierarchical planning, specifically on the use of constraints to represent the interactions between subproblems (e.g. Stefik 1981a, 1981b). A pleasant chat on the flight led us to realise we were going to the same conference so we shared a cab ride to our destination. Dropped off at the conference hotel, Mark met up with many of his Stanford colleagues and among them was Barbara Hayes-Roth. She took an interest in my open questions about how to go about building a KBES for site layout and suggested that I touch base with her back at "the farm" (the Stanford's had a horse farm prior to establishing a university campus). She suggested I look into using the

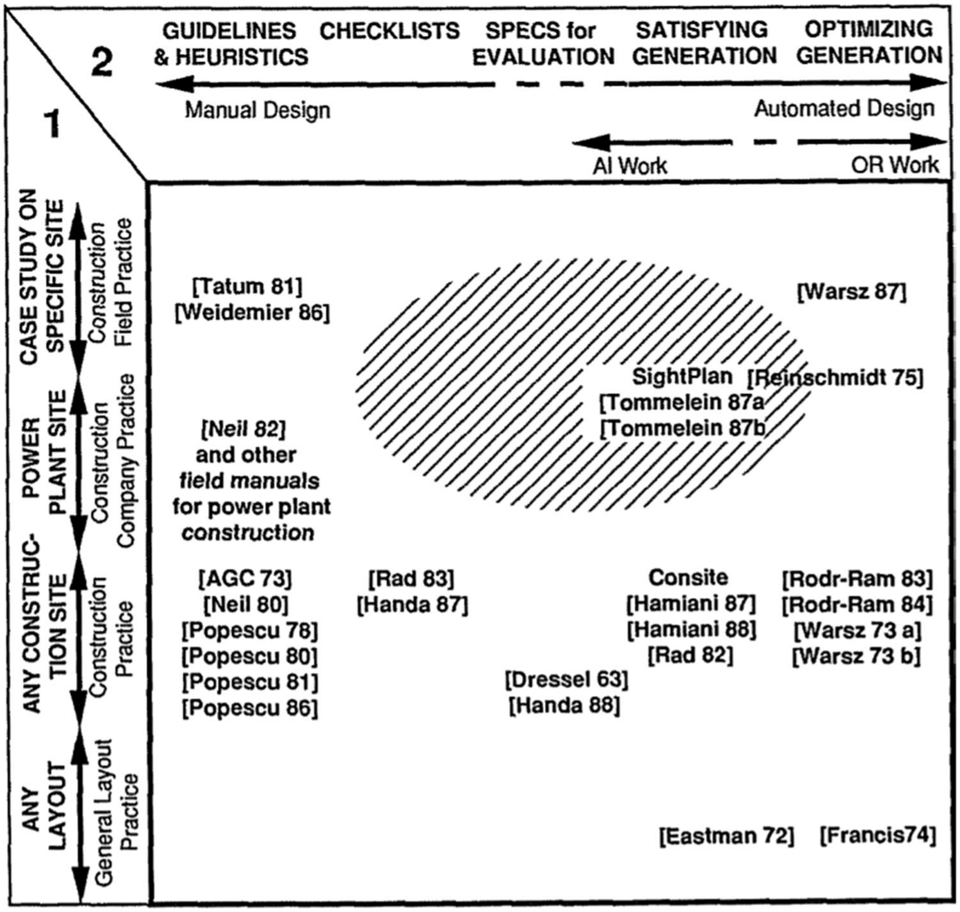

Figure 6. Literature on site layout charted by (1) How general or domain-specific the described work is, versus (2) Whether the described method is applied in manual or computerised layout generation (Figure 2.5 in Tommelein 1989).

blackboard system framework she had developed to address arrangement assembly tasks (Duncan *et al.* 1986). She had not thought of construction as a domain to work in, but she saw similarities between site layout and protein-structure modelling that piqued her interest. It took me several more months of literature review (Figure 6) and pondering the research question and possibilities, before deciding to make an appointment with her. The rest is history: an "accidental" meeting led to a fruitful inter-disciplinary collaboration.

The concept of programming a blackboard model originated in the work of Raj Reddy at Carnegie Mellon University, who developed a framework for speech understanding (Reddy *et al.* 1976). The speech understanding task required processing of different kinds of knowledge with multiple representations and at multiple levels of abstraction. Recognising a lack of knowledge on how to combine these into an expert system, the idea was to define each one on their own and then arrange them as in a collaborative classroom-like setting to have them all work at the same time, and make contributions on the blackboard whenever they could. Hayes-Roth (2015) recounts: "This was a very opportunistic model of how to bring disparate types of knowledge to bare on a hard problem. We thought that was a good way for planning."

In turn, Barbara leveraged this opportunistic model of control to describe the task of errand planning (Hayes-Roth and Hayes-Roth 1979). Her view on planning was that "You don't need to make your plan and [then] execute your plan: You are always executing. You are always planning" (Hayes-Roth 2015). At the level of control (deciding what to do next), this meant that knowledge sources would look at a situation, always changing, and assess: if the plan is good now, then charge ahead, else modify the plan. This view suits the task of (layout) planning in construction very well.

March and Smith (1995, p. 257) wrote "A model is a set of propositions or statements expressing relationships among constructs … A model can be viewed simply as a description, that is, as a representation of how things are … In our [design science] framework, however, the concern of models is utility, not truth." They proceed: "consider the research in expert systems where knowledge is modelled as a set of production rules or frames (Lenat and Davis 1982). Although proposed as a model of human expertise (i.e. a cognitive science theory), from a design science point of view, it is irrelevant if humans actually represent knowledge in this way. The concern is if this type of representation is useful for the development of artefacts to serve human purposes. While expert systems research has been criticised for abandoning "basic research on intelligence" (Hofstadter, quoted by Weber (1987)), its design science impacts are irrefutable."

Exactly in line with this observation, the SightPlan work started by capturing expert knowledge and translating it in terms of a strategy for BB1 to follow, i.e. the early-commitment strategy. However, due to the number of possible arrangements we realised the computer could augment human decision-making by keeping track of them so we created an alternative and experimented with postponed-commitment strategies.

This choice of model then led to deciding and articulating the objects of knowledge that would be needed.

Activity 3: define the objects of knowledge

The objects of knowledge (per Voordijk) are categorised further by March and Smith (1995) who instead use the terms constructs and conceptualisation, models, methods, and instantiation.

Constructs and conceptualization

Conceptualizations … define the terms [the vocabulary of the domain] used when describing and thinking about tasks. They can be extremely valuable to designers and researchers. Brooks (1987), for example, discusses the transformation in thinking about the software development process when presented with the conceptualisation of *growing* rather than *building*. When software is built, one expects to specify the entire plan in advance and then construct the software according to plan. When software is grown, it is developed *incrementally*. Functionality is added as it is needed. The software developer conceives of the product as being dynamic, constantly evolving rather than as a static entity that is "completed" at a point in time. On the other hand, conceptualizations can blind researchers and practitioners to critical issues…. (March and Smith 1995, p. 256, italics in original text).

Barbara's idea of "always executing, always planning" and simulation of opportunistic reasoning as an alternative to using algorithms resonated with what I had learned by then about layout planning. We thus developed the system based on the opportunistic application of "technological rules" (Bunge 1967), defined at the domain level (e.g. Where to position a laydown yard?) and also at a meta level (e.g. How to go about deciding which types of objects to position first?). A number of supporting constructs then had to be developed, namely:

Site layout objects (temporary facilities): the objects of interest (e.g. laydown yards and areas to locate equipment) were abstracted so they could be represented by rectangles.

Layout practices (expert knowledge): The knowledge acquisition phase of the research process included reviewing the literature (a descriptive research approach) and interviewing construction managers (an interpretive approach as advocated by e.g. Seymour *et al.* 1997) in order to translate their tacit knowledge and beliefs (including heuristics) of how to go about layout planning into rules to be coded in a rule-based expert system. Extensive discussion in the KBES community at the time addressed concerns about knowledge verification and validation so as to ascertain the KBES' ability to address the problem at hand.

Spatial prepositions: The study of spatial prepositions was a necessary research step because the domain experts I interviewed in the knowledge acquisition phase expressed their rules and heuristics using natural language (e.g. "The laydown area needs to be *adjacent* to the road."), and I was to codify those words and expressions (e.g. *adjacent*) as rules and constraints in the KBES.

Taking a computer science class with John Sowa, who had developed conceptual graphs to formalise the structure of natural language as a means to structure database systems (Sowa 1984), spurred me to study the use of natural language to express two-dimensional spatial relationships by means of conceptual graphs. This study addressed the ambiguity of spatial prepositions in English and additional ambiguity when translating such prepositions from one language to another (Tommelein and Gupta 1987). It highlighted the need to greatly simplify how space would be represented in SightPlan. We decided to use rectangular objects to represent temporary facilities and express two-dimensional spatial relationships using Manhattan distances (also known as rectilinear distances).

While this study on 2D spatial prepositions was fundamental to the research on SightPlan, it subsequently also informed the work of other researchers, who formalised ontologies for natural language processing (e.g. Lambert *et al.* 2008).

Geometric constraints: Pragmatics were needed to map spatial prepositions to computable 2D constraints.

2D bounded intervals: a computation engine GS2D (Confrey and Daube 1988) was programmed based on a bounded interval representation to model spatial constraints, so that SightPlan could pursue a least-commitment strategy in the blackboard model. This programming was informed by the 3D computational approach developed to for PROTEAN.

Method

"A method is a set of steps (an algorithm or guideline) used to perform a task. Methods are based on a set of underlying constructs (language) and a representation (model) of the solution space" (March and Smith 1995, p. 257; also see Gericke *et al*. 2017). In the case of SightPlan, the method was arrangement assembly based on constraint satisfaction. This required articulation of the aforementioned constructs, including the rules for layout, the language to map spatial prepositions to geometric constraints, etc.

Instantiation

An instantiation (or instance) is a specific example, application, or embodiment of concepts that are presented abstractly in a (hierarchical) classification system. The instantiation of the constructs, model, and method for spatio-temporal reasoning to create site layouts was SightPlan.

Activity 4: define the characteristics of the results

In line with Newell and Simon's (1972) notion that the study of instantiations in computer science is an empirical discipline (cited in March and Smith (1995)), we programmed SightPlan to pursue two assembly arrangement strategies, and then compared and contrasted them: (1) one pursued early commitment and (2) the other one postponed commitment (Tommelein 1989, Tommelein *et al.* 1991). The former strategy emulated the expert's approach to layout planning, by capturing their rules-of-thumb as KSs. This approach might produce a result but, as modelled in SightPlan's rules, could not guarantee to find one even for an under-constrained problem (meaning that one or more and possibly infinitely many solutions exist) because the system did not have any rules for backtracking. We did not implement backtracking because it seemed computationally costly compared to using a bounded-interval based approach. The latter strategy kept track of all possible positions of all layout objects while successively applying constraints. As a result, an under-constrained task could yield infinitely many possibilities and a SightPlan user could then provide more input to further narrow the solution set.

Activity 5: define the quality criteria

A number of quality criteria were applied to SightPlan. One quality criterion for the artefact was: Can the system create a solution, provided one exists? Of course, in case the task were over-constrained, no solution would exist. But otherwise, SightPlan's postponed-commitment strategy would yield at least one, and depending on the situation possibly infinitely many possibilities, from which the user could then select.

The validation process of SightPlan included having a domain expert who had been involved in one of the case projects (IPP) assess the system's performance. The expert acknowledged that SightPlan was able to construct a (set of) solutions, but immediately grabbed for the mouse and wanted to start moving objects around in order to visualise other alternatives. It was as clear then, as it is now, that people want to use computer programmes to help sharpen their intuition and inform their decision-making. Human-machine interface design is important to allow for the meaningful interpretation of modelling results.

If the validity of the early-commitment strategy was gauged based on its capability to generate a solution layout that resembles the layout generated by the field expert, then that strategy succeeded quite well. SightPlan constructed the layout of the IPP project in many ways akin to the expert's. We also tested the model on a second project (American 1). However, the model failed in that we had not provided it with all the constraints. Of note also is that we had no means of telling which arrangement was the better one, or in general, how good a satisfying arrangement is. Objective criteria should be defined, but even the domain expert involved in SightPlan's validation process had no guidelines to offer.

If the validity of the early-commitment strategy was gauged based on how well it represented the actions taken by a field expert, then we could not assess that because we did not have records on exactly how the expert designed the layout. It is also possible that different experts would do it differently.

If the validity of the early-commitment strategy was gauged based on how well its layout process can be understood by practitioners, then SightPlan succeeded. Showing SightPlan to the Field Construction Manager from the IPP project yielded good

Table 1. Research framework with SightPlan instantiation (after Figure 1 in March and Smith 1995).

	Research activities [aka. design process]			
	Design science		Natural science	
	Build	Evaluate	Theorise	Justify
Research Outputs [aka. Design Artefacts]				
Constructs	• Site layout objects (temporary facilities) • Layout practices (rules) • Spatial prepositions (Tommelein and Gupta 1987) • Arrangement constraints • 2D bounded intervals (Confrey and Daube 1988)	☒		
Model	BB1	☒	BB* (Hayes-Roth *et al.* 1986b, 1986c)	
Method	Opportunistic planning of arrangement assembly using constraint satisfaction with (1) early-commitment strategy, (2) postponed-commitment strategy, and (3) temporal strategy	☒		
Instantiation	SightPlan	☒	Learning from PROTEAN, SightPlan, Guardian	

conversation about items SightPlan has missed but also the remark that SightPlan did a pretty good job despite its limited amount of domain knowledge.

Having described SightPlan based on five knowledge-generating activities, the system is next framed from a design science perspective along the dimensions of research activities vs output produced.

Methodological steps of design science and SightPlan instantiation

Characterisation of design science research

The research methodology we followed to create SightPlan fits well in the two-dimensional framework of research activities vs output produced, that March and Smith (1995, p. 251) presented for research in information technology (IT). The horizontal axis in Table 1 describes four research activities: (1) build and (2) evaluate, which belong to design science, and (3) theorise and (4) justify, which belong to natural science. "Build refers to the construction of the artefact, demonstrating that such an artefact can be constructed. Evaluate refers to the development of criteria and the assessment of artefact performance against those criteria. […] [T]heorize refers to the construction of theories that explain how or why something happens. In the case of IT research this is primarily an explanation of how or why an artefact works within its environment. Justify refers to theory proving. It requires the gathering of scientific evidence that supports or refutes the theory" (1995, p. 258). March and Smith (1995) stated that "both design science and natural science activities are needed to insure that IT research is both relevant and effective." The vertical axis in Table 1 describes the broad types of outputs produced by design research, namely (1) representational constructs, (2) models, (3) methods, and (4) instantiation.

Table 1 shows that the SightPlan research addressed all dimensions in the framework that pertain to design science. Its contributions to natural science were not so fully spelled out.

Having characterised the SightPlan system from a design science perspective by way of example, the next section offers reflections on research methodologies used in CME.

Reflections on research methodology

Not often does one get the opportunity and have the time to dissect and analyse one's research work, so many years after it was conducted, and then frame it in ongoing discussions about research methodologies suited for research in CME. In this case, the framework for analysis included Voordijk's (2009) five dimensions of knowledge-generating activities combined with March and Smith's (1995) framework for information technology that categorises research activities (process steps of design science and natural science) vs. research outputs (design artefacts) (Table 1).

The SightPlan research was based on the positivist premise that a KBES could be developed. The methodology we followed to develop this socio-technical artefact, namely a decision support system for construction site layout, offers an illustration of one of several such types in the design-science genre (Peffers *et al.* 2018).

The research started as a collaboration between civil engineers and a cognitive scientist, and involved fellow students in computer science, all with an artificial-intelligence mind set. As such, conducting the research required significant effort and time dedicated to the interpretive process that included formulating the knowledge requirements, narrowing the selection of project types, identifying domain expects, studying knowledge acquisition practices and potential pitfalls, conducting on-site interviews, and formalising natural language utterances. This effort resonates with Seymour *et al.*'s (1996, p. 119) call for researchers in construction management to not "underestimate or ignore the importance of the interpretive process." However, conducting the research also required development of an artefact, the SightPlan system. This was realised using a design science methodology, a rationalistic process. Finally, the research included developing graphical interfaces to help people interpret the results produced by the computer. That a combination of these were pursued is in line with Chau *et al.*'s (1998) argument in favour of methodological pluralism and others who countered Seymour *et al.*'s (1996) provocation (e.g. Raftery *et al.* 1997, Runeson 1997, Rooke *et al.* 1997).

In information systems (IS) research, design science is presented as a paradigm different from-, yet complementary to behavioural science (which may include or at least relates to cognitive science). "The behavioural science paradigm seeks to develop and verify theories that explain or predict human or organisational behaviour. The design-science paradigm seeks to extend the boundaries of human and organisational capabilities by creating new and innovative artefacts. Both paradigms are foundational to the IS discipline, positioned as it is at the confluence of people, organisations, and technology. (Hevner *et al.* 2004, p. 75)" Arguably, CME research finds itself to be in a similar position. In my view, and also argued by others (e.g. Lee 2000 cited in Hevner *et al.* 2004), the two are inextricably intertwined. Accordingly, researchers in CME have a rich menu of research methodologies to choose from.

Research efforts can make a contribution to knowledge in several ways. Gregor and Hevner's (2013, Figure 3) differentiate contribution opportunities in a two-by-two matrix based on application domain maturity vs. solution maturity. Routine design takes place when both are high, in which case no major knowledge contribution is made. However, in the remaining three quadrants, a contribution can be made: (1) improvement involves developing new solutions for known problems, (2) exaptation involved extending known solutions to new problems, and (3) invention involves coming up with new solutions for new problems. The SightPlan research contributed in two quadrants, with parts of the system being novel and many others not. To highlight two contributions, for example, in quadrant (1), the known problem was site layout (and related literature on which to build) and the new solution was KBES-based arrangement assembly; while in quadrant (2), the BB1 system and its language to express arrangement assembly relationships (ACCORD) were the known solution developed for PROTEAN and these were applied to the new site layout problem addressed by SightPlan.

CME researchers may find it useful to spell out their research in terms of the objects of knowledge (constructs and conceptualisation, models, methods, and instantiation) as was done in this paper to describe SightPlan, and try to fit them in this matrix in order to articulate their contributions to knowledge. Since a researcher's work is informed by work done by others, contributions will likely build on other people's work. In turn, contributions may constitute new building blocks that they or others can further develop into theoretical constructs.

Open-minded researchers in CME will inevitably find themselves exploring building blocks developed in "adjacent fields of study" (e.g. Volker 2019) and possibly also contributing to those fields. While adjacent is spatial preposition to be disambiguated (as so many are, e.g. see Tommelein and Gupta 1987) in this context, suffice it to say that the exploration will start wherever the researcher chooses to position themselves in the search space, unimpeded by the determination of what is "in" or "out." CME is a broad-based cross-disciplinary field, as this journal has recognised (e.g. Dainty and Leiringer 2019).

Summary and conclusions

The SightPlan model development and experimentation demonstrated how and to what extent one can emulate the steps taken by a domain expert performing layout design. In addition, it demonstrated how a computer can be programmed to support set-based design (in this case, to track sets of feasible locations of layout objects), and how interactive graphics combined with an expert system can augment human decision-making. Thus, the output of this multidisciplinary design science experiment resulted in, following Voordijk's (2009) categorisation, "concepts that specify what to do, if a certain result is to be attained under given circumstances (functional rules), and insights in the interrelationship between design, production and operation of the built environment and social practice (socio-technological understanding)."

The design science methodology followed to develop the SightPlan system offers a cogent illustration of these points. Whereas the initial objective of our work was to learn how people go about laying out temporary facilities on construction sites, explore AI architectures, and for me to conduct PhD-level research, our team's expertise in the domain of construction management on one hand, and in the domain of cognitive science on the other hand, shaped our research as it progressed. Through descriptive- and interpretive research we learned how people go about laying out temporary facilities on construction sites. In the course of developing SightPlan we learned about opportunistic and collaborative planning as emulated by the blackboard system framework by applying it to a task in the domain of construction management. Then we experimented with alternative approaches for solving arrangement-assembly problems to help overcome human cognitive limitations, and developed a graphical user interface to support human decision makers. As described, it resulted in the building and evaluation of a KBES, that is, a system that embeds functional rules, instantiated specifically to help layout temporary facilities on construction sites. This met a goal of design science, which is "to develop knowledge that the professionals of the discipline in question can use to design solutions for their field problems" (Van Aken 2004).

The crossing of research paths in civil engineering and cognitive science created a win-win situation. In fact, Ray broadened his collaboration with Barbara to study construction plan generation using the BB1 architecture (e.g. Darwiche *et al.* 1988) while separately tackling AI-based planning in general (e.g. Kartam and Levitt 1990). This was around the time that he was instrumental in founding the Centre for Integrated Facility Engineering (CIFE) at Stanford. His interest in computing and simulation later turned towards organisational modelling (e.g. Jin and Levitt 1996).

In addition, the SightPlan research contributed to deepening socio-technological understanding as it pertained not only to how people address the site layout problem, but more broadly also to spatio-temporal reasoning, arrangement assembly problem-solving, and distributed decision making as modelled using the BB1 framework. The limited degree to which the site layout problem was really addressed (e.g. SightPlan did not have rules to size temporary facilities) opened the door for me to further study human-machine interfaces while also, in the domain of CME, extend my research from layout to materials management, supply chain management, and lean construction (Tommelein 2015).

Having described the design science methodology pursued to develop the SightPlan instantiation, thereby adding to the CME community's ongoing discussion on research methods, and having described the semi-rational turns taken in its development, to close this paper, a few words of reflection on Ray's work as a researcher and PhD-student advisor are in order. While PhD students tend to start their journey by wanting to search, find, and tackle that all-important research question, hoping their solution will have an earth-shattering impact, much of the value derived from being on a PhD-student journey stems from learning to master the research process, to pursue the journey. This includes developing one's questioning skills, opening up to new concepts and ideas, acquiring rigour in using certain research methodologies, applying them judiciously, and then learning how to document and share findings.

I am most indebted to Ray for guiding me along this journey. I am confident that other advisees of his will concur that he exercises great patience in developing his students' talents, promoting openness to new ideas and sparking curiosity in them while engaging them in thoughtful deliberation to question current thinking and pursuing scholarly rigour in exploring new thinking. In all regards, my PhD-student journey was terrific. Thank you Ray!

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