# CUE-BASED DECISION-MAKING IN CONSTRUCTION WORK CREWS: AN AGENT-BASED MODELING APPROACH

By

Ali Lahouti

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ABSTRACT

CUE-BASED DECISION-MAKING IN CONSTRUCTION WORK CREWS:
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Construction work crews often deal with ambiguities (e.g., mismatch between provided directives and existing situations) at the work face about 'what-to do'. In such a circumstance, the work crew is forced to interpret cues present at the work face surroundings to make a decision. This research argues that dynamics of a construction work crew, as a collection of two or more skilled trade workers who are continuously engaged in face-to-face interactions influence its interpretation of work face cues. Dynamics of a construction work crew may be adapted to the group Input-Process-Output (I-P-O) framework where inputs such as characteristics of each member enable and/or mediate a group's process like communication, and interaction to generate outputs – e.g., a decision.

A population of one hundred and seventy six (176) construction skilled trade workers were qualitatively interviewed: (i) to learn their most-immediate actions in a situation where directives did not match the work face condition and while physical hints were present; and (ii) to identify input factors they experienced to be influential on the process of decision-making and their interactions to determine 'what-to do'. Contents of these interviews were clustered in categories of implied descriptions, 69 percent of which suggested that these work crews were more eager to autonomously resolve the ambiguity and most-likely by discussing the issue with their crew-mates instead of contacting their supervisors (25%), or customers (5%). Contents of these interviews also revealed that knowledge and skill of crew members, their confidence and trust in others crew-

mates, and their open-mindedness were discussed most frequently as impactful factors on decision making and interactions between members.

In order to understand impacts of these input factors on interactions between work crew members and their interpretations of cues, an Agent-based Modeling Simulation (ABMS) was developed. The abstract ABM (in NetLogo environment) simulated a work crew of two members with uniformly-distributed levels of skillfulness, confidence, and open-mindedness who were to complete an activity by making decisions on initiating a series of tasks. The crew operation time, amount of rework it conducted, and frequency of its call-for-assistance were measured for 199,948 cycles and were analyzed with respect to input factors. Skillfulness was identified as the most influential factor on operation time. It was also realized that all three outputs measures were most sensitive to input factor skillfulness; and that each output measure was almost equally influenced by variation of the factors confidence, and open-mindedness.

The research dissertation concluded that variations (or rather heterogeneity) of skillfulness, confidence, and open-mindedness in work crews would increase intensity of interactions between members, and would, thus, decrease the likelihood of expected optimum operation time, no rework, and less frequency of call-for-assistance.

The core of this research dissertation offers a sound basis for construction work crew recruitment by identifying knowledge and skills as an intuitive requirement while screening for additional traits of confidence, and open-mindedness. It also provides an explanation to better understand ‘why’ the Last Planner® System (LPS®) of Project Planning and Production Control is instrumental in maintaining a reliable, and predictable workflow for a construction operation.

To my late father, *Hassan Lahouti*,
who taught me education is not as much about learning facts as is about training minds to think;

and

To my loving, and caring mother, *Fatemeh Lahouti*,
the cornerstone of my life, who by example taught me it is not what one gathers but scatters in life that will tell the story of life he or she lived.

## ACKNOWLEDGEMENTS

Teachers enable their students to learn by enlightening them to understand principles, and by indulging them to experience facts. And I do believe that those principles, and facts are not only lessons one learns in classrooms but also the morals he or she takes away from each encounter.

I am very fortunate to have been taught by a thoughtful teacher, a careful scholar, and on top of all an honorable friend: Dr. Tariq S. Abdelhamid, Associate Professor of Lean Construction. As words simply will fall short in articulation, thanking him for his academic advisement, his professional leadership, and his friendly mentorship is merely acknowledging the value of standing, unconditional support this gentle man has offered me – specifically during inevitable, and sometimes unfortunate events of life. I hope one day I can pay it forward.

I wish to offer a sincere thank you to my advising committee faculty: to Dr. Patricia L. Crawford, Associate Professor of Landscape Architecture, who taught me that each of our endeavors has its own merits. Whether it was a classroom discussion, a research meeting, or a professional conversation, her actions, and reactions always encouraged the ‘worthiness’ in me; to Dr. Arika Ligmann-Zielinska, Associate Professor of Geography, Environment, and Spatial Sciences, who by example taught me that teaching is not filling others with information but releasing your own knowledge; and to Professor Timothy L. Mrozowski, Professor of Construction Management who taught me patience in our long, spirited debates.

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crew who enthusiastically shared with me their years of experience to shape the platform for this research dissertation.

And last, I wish to offer my most special thank you to Dr. Mahmood M. Moallemian, who has, in difficult moments of my life, stood by me as a true friend; supported me like a parent; and advised me as a mentor. I am, for life, in his debt.

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# KEY TO SYMBOLS

| Symbol | Description and Representation |
|---|---|
| Data | Information that enters (i.e., input) to be processed in a system; result that leaves (i.e., output) as consequences of a system conduct, and process |
| Decision | A conditional step; an emerging point for inputs |
| Process | An action; a task is performed |
| Start / End | A system initiation; a process termination |
| Sub-Process | A sequence of steps – that itself is a system |
| → | Transfer of temporary control from a unit to next; passage of state between consecutive units |

# (1) Introduction

## (1.1) Overview

Construction work crews often face ambiguities while completing an activity. These ambiguities may be caused by incomplete construction drawings, missing/incorrect/misinterpreted information, an implicit verbal instruction, etc., which do not provide an ideal state that this dissertation research refers to as “perfect information”. When a work crew does not receive complete instruction and perfect information, that work crew tends to gather, look for, and/or leverage physical hints (which this thesis will specifically refer to as cues) existing at the location of work in order to make sense of and augment the incomplete instruction and imperfect information.

This investigation will focus on the situation when a construction crew encounters ambiguities during the execution of work on the job site. The conjecture of the research dissertation is that the construction work crew will make use of the existing physical hints (cues) to augment the missing information. The cue can be deceiving and may present a challenging process for the work crew members. This challenge intensifies the interaction among crew members to proceed with the work; and the interaction in turn impacts the interpretation. How all these dynamics eventually impact work execution, from the view-point of time and cost, is not well understood and (definitely) is not quantified with respect to resource utilization.

## (1.2) Significance of problem

Resources (e.g., work crew; material; etc.) are utilized in delivering any construction activity. When interpretation of a cue(s) causes deviation from expectation, and therefore the anticipated outcome is not delivered due to an error(s) or rather misinterpretation, then more resources – at least twice as much – will have to be employed to accomplish the same activity correctly. In the general sense, this over-use/re-use of resources can at the least include:

(a) removing wrong work installed right is a waste of resources. It is a necessary task to be done and, yet, of no value as it was not planned to exist;

(b) rework can be recognized as another consequence. A biased interpretation of an instruction and making a decision based on a readily-available cue may result in an undesired – i.e., wrong or incomplete – outcome which will require a do over. This exceeding quantity of resource utilization can at least introduce as three times budget-over run and two times task duration delay for what is initially planned for this task – let alone its impact on over-all schedule performance;

(c) delay may be another consequential waste. When a cue from the surroundings is used in decision-making and a wrong thing is conducted (i.e., an undesired outcome), delay can be experienced either due to unavailability of required work to the successor task or due to some schedule slippage as a result of mandated re-work.

When this concept is associated with construction project management productivity performance, the importance of sufficient information and the impact of cue interpretation are very critical as the cost of re-work due to absence of explicit instructions is magnified.

## (1.3) Problem Statement

*One*: When a work crew encounters a physical hint or a cue, that work crew practically interprets the cue to fill in for the missing instruction and then makes a decision about 'what-to' do (Lahouti & Abdelhamid, 2012). This decision on 'what-to' do may not align with the original intent. Therefore, the work crew may '*do the wrong thing right*': (i) it is the 'wrong thing' because cue-interpretation can interrupt the alignment between the 'what-to' that the crew ends up completing and that the original instruction intended; and yet (ii) it will be done 'right' because the work crew is (expected to be) appropriately skilled to deliver the 'what-to' that the complete original instruction intended.

On the note of *doing the wrong thing right*, it is important to state that the problem is not about technicality of the 'what-to'; it is not about how to execute; it is not about application of rules and laws; it is not about the craftsmanship; it is not about equipment break-down and/or availability; it is not about planning. In fact, the problem is about the final description of a 'what-to' do; it is in the search by a crew to define the task at the location of work immediately before it is executed; it is the fine-tuned description of 'what-to' do based on what makes sense on the job site.

The point of departure from previous researches (Lahouti & Abdelhamid, 2012; Lahouti, 2013) is the consideration of work crew size. Lahouti and Abdelhamid (2012), and Lahouti (2013) discussed interpretation of cues and physical hints on construction a job site with the assumption of a one-member work crew. This research dissertation releases this assumption and considers a work crew of more than one members.

*Two*: In a construction project, activities/tasks are performed in small group settings. Therefore, each work crew may be considered a representation of a small group. Group consultation, or rather interaction, is a common characteristic of a small group. This common, instinctive behavior can be prompted in a small group by variety of factors. As illustrated in Figure 1.1, interactions in a group may be influenced in some fashion by families of individual (e.g., experience; skills), group (e.g., hierarchy; size), activity (e.g., complexity; difficulty), and environment (e.g., strategic location) factors.

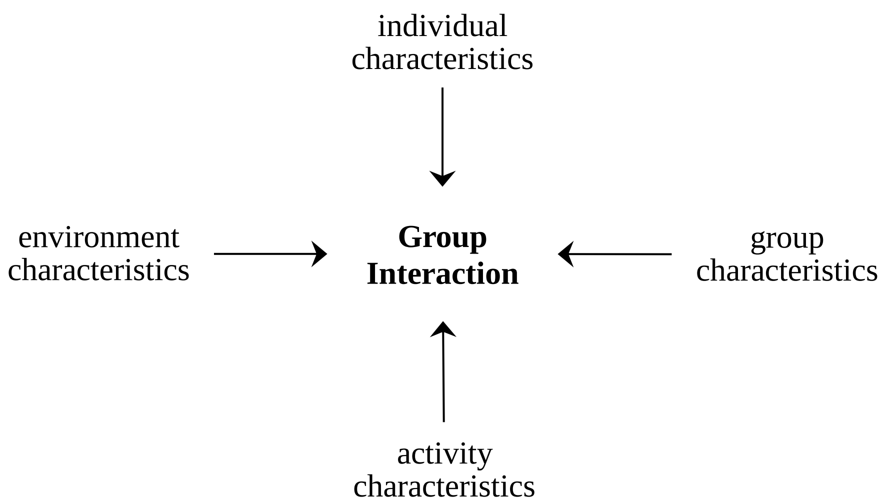


Figure 1.1 – Category of Factors Influencing Interactions between Group Members
Adopted from Source: (Forsyth, 2014, p. 408)

A decision is an example of an immediate output of a small group interaction mediated by these categories of factors. As conceptually presented in Figure 1.2, members of a construction work crew, an example of a small group, interact to plan the tasks required for completion of their assigned activity, reach consensus on tasks to conducted, and make a decision(s) as to initial action.

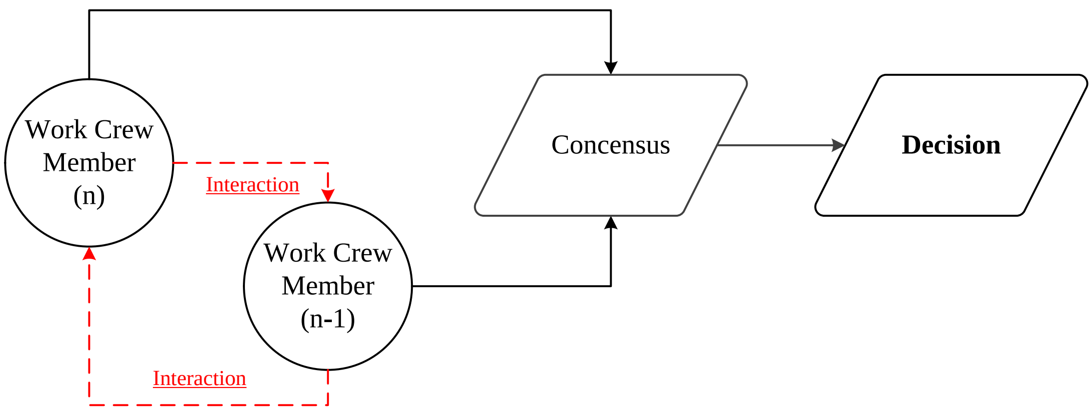


Figure 1.2 – Conceptual Representation of Group Decision-Making

Combination of claims _One_ and _Two_ can be stated as:

In a construction project, when a work crew receives incomplete instructions about 'what-to' do, it prompts the interaction(s) between members of that work crew for two apparent reasons: (i) there are pieces of information missing in the instruction; and (ii) there is (almost always) a physical cue(s) present at the job site – which may substitute for the incompleteness of instruction. As Figure 1.3 depicts, the output of this interaction(s) is interpretation of the cue(s). A decision, which is based on cue-interpretation, will then define the 'what-to' that will be executed on the job site. Such may define the relationship between group and its task. That is, how a group responds to its activity following the interactions between its members. It should be noted that interaction refers to processes such as information acquisition, information processing, decision making, etc.; and that since interactions between members of a work crew are influenced by different factors, it is rational to also claim those factors influential on interpretation of cues and physical hints.

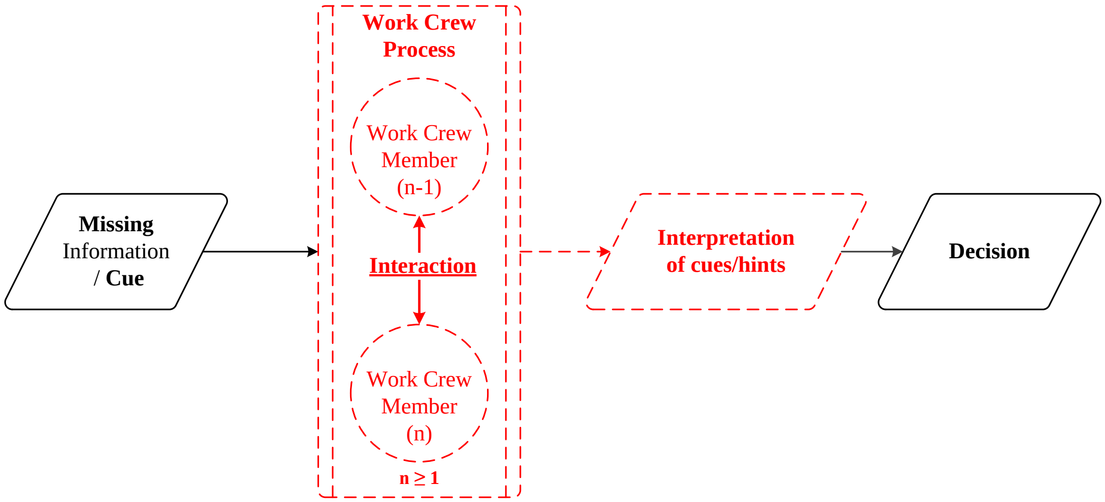


Figure 1.3 – Schematic Process Map for Cue Interpretation in a Construction Work Crew

## (1.4) Goal and Objectives

The overall goal of this research is to better understand the impact an incomplete instruction and an imperfect piece of information will impose on production performance on a construction job site. More specifically, it aims to understand how interactions between work crew members may influence interpretation of cues and physical hints on a construction job site; and to investigate whether a relationship exists between interactions of work crew members and interpretation of a cue when the work crew receives an incomplete instruction and imperfect information. To approach this goal, the following achievable objectives were followed:

(1) a questionnaire was developed to identify factors that influence interactions between work crew members, and its outputs;

(2) a strategy was developed to introduce the factors identified in Objective (1) into a computer simulation package and in order to form a model and simulate interaction among construction work crew members;

(3) an Agent-based Modeling Simulation (ABMS) was developed, and simulation results were analyzed to determine whether a correlation existed between work crew interaction and interpretation of a cue: key outcomes (i.e., amount of time spent; rework generated) were measured.

## (1.5) Dissertation Research Outline

This dissertation research is divided into six (6) chapters:

In Chapter One the research problem was stated, its significance was discussed, and objectives were proposed in order to approach the investigation goal.

In Chapter Two literature on topics of *Small Groups*, *Group Dynamics*, and *Group Performance* are surveyed: the term *Group* is defined, its properties discussed, and a reference conceptual framework for *How Group Works* is reported. The literature on construction project research is also reviewed on *information* and *instruction* – which were concluded to be necessary resources for construction activities in project operations. It is further discussed that lack of information and instruction would encourage construction work crews to improvise and utilize available resources in their surroundings, and to interpret cues and physical hints in order to fill the missing pieces of information; to make a decision and proceed; and technically to make-do.

In Chapter Three methods by which this dissertation research was conducted are explained: how factors influential on work crew members' interactions when interpreting incomplete instructions were identified; and how such interactions and decision-making were simulated using Agent-based Modeling Simulation (ABMS).

Chapter Four begins with a discussion on whether characteristics of a construction work crew would satisfy group's criteria; and how group's Input-Process-Output framework would fit a work crew. Then, contents of qualitative interviews with construction work crews are analyzed, and influential factors are reported as a portion of dissertation research findings.

In Chapter Five outputs of the Agent-based Modeling Simulation (ABMS), developed based on findings reported in Chapter Four, are analyzed and reported as a portion of dissertation research findings.

Chapter Six concludes this investigation by re-stating the problem of interest, and its objectives, reviewing the need for this research with respect to existing academic literatures, and summarizing and comprehensively discussing the findings of research methods. Limitation of research conduct, contributions of findings to body of construction-industry (academic and professional) knowledge, and opportunities for further development of this work are also deliberated.

## (2) Background and Literature Review

As stated in section (1.3), this dissertation research suggested that a construction work crew, when faced with ambiguity, would make use of cues and physical hints available and/or existing in its surroundings to augment the missing information. The main concepts in this statement – as Table 2.1 summarizes in two sections – are (1) a construction work crew, and (2) decision-making in a construction work crew.

The speculations about these two main concepts are: (i) that a construction work crew is a group; (ii) that such challenges (of ambiguity) intensify interactions between members of this work crew; and (iii) that these interactions, in turn, impact interpretation of the situation (i.e., decision-making). The following research questions were considered to investigate these claims:

(1) Does a construction work crew meet required criteria and qualifications to be a group?

(2) How does a construction work crew function from the perspective of a group?

(3) What independent factors (i.e., initial states and mediators) do influence a construction work crew performance? And which of those influencing factors are critical on a work crew's performance in presence of cues and physical hints?

(4) How does completeness of information and explicitness of an instruction, or its lack thereof, play a role in executing an activity in a construction project operation at its crew level?

(5) How may correlation between interpretation of a cue and interaction of a construction work crew members be investigated?

Table 2.1 – Foci of Survey in Existing Literature

| **Section One: Construction Crew as a Group** | | | **Section Two: Decision-Making in a Construction Crew** | | |
|---|---|---|---|---|---|
| *Question (1)* | → | Group Characteristics | *Question (4)* | → | Group Performance |
| *Question (2)* | → | Group Functions | *Question (5)* | → | Group Analysis |
| *Question (3)* | → | Group Variables | | | |

Section One: Construction Crew as a Group

*Question One: Does a construction work crew meet the required criteria/qualifications to be addressed as a group?*

Answering this very question requires a general understanding of a group – and what a group is.

(2.1) Definition of a Group

Social Scientists – those who study groups – have not agreed on a comprehensive description of the term *group*. However, they have defined it with respect to varying interests of their specific research. That is, no unique approach has been employed to describe the concept *group*. In fact, some have defined a group based on its characteristics as a unit. Table 2.2 presents two of such definitions.

Table 2.2 – A Sample of *group* Definitions Focused on *Concept*

| **Definition** | **Source** |
|---|---|
| "A dynamic whole based on interdependence" | (Lewin, 1948, p. 184) |
| "An intact social system … interdependence for some shared purpose" | (Hackman & Katz, 2010, p. 1210) |

While some researchers have expressed a group "at a great length", others have found it more appropriate to define a group by emphasizing "one (or a few) of the many characteristics" it possess (Shaw, 1981, p. 4). In other words, researchers have chosen certain properties of interest and have studied groups accordingly. In this latter approach, in contrast with the former one, focus is on constituent elements of a group as the unit of analysis. As summarized in Table 2.3, for example, *commonality* of a goal, a norm, and perception among members of a group are the main characteristic which has been emphasized by some researchers.

Table 2.3 – A Sample of Characteristics Focused in Group Definitions

| **Focus of Definition** | **Source** |
|---|---|
| Commonality of goals, norms, and perceptions | (Smith, 1945, p. 227); (Newcomb, 1951, p. 3); (Mills, 1967, p. 2); (Cartwright & Zander, 1968, p. 46); (Mabry & Barnes, 1980, p. 4); (Foley & MacMillan, 2005, p. 21); (Forsyth, 2014, p. 400) |
| Interaction, and interdependence | (Bales R. F., 1950, p. 33); (Cartwright & Zander, 1968, p. 46); (Merton, 1968, p. 339); (Crosbie, 1975, p. 2); (Shaw, 1981, p. 8); (Shaw, 1981, p. 8); (Jackson, 2010, p. 317); (VandenBos, 2015, p. 471) |
| Relationship | (Brodbeck, 1958, p. 2); (McDavis & Harari, 1968, p. 237); (Davis, 1969, p. 4); (McGrath, 1984, p. 8); (Syer & Connolly, 1996, p. 7); (Forsyth, 2014, p. 4) |

In another instance, several researches have selected *interaction* – which is a form of *interdependence* (Cartwright & Zander, 1968; Shaw, 1981) – as the criterion of investigation; and have stressed that in their descriptions of a *group*. Or many social scientists have focused attention upon *relationship* as an essential characteristic to describe a group. Although *size* is a single characteristic that is unanimously emphasized, these definitions each signifies one (or a few) of many different characteristics in a *group* which has attracted social scientists, and explicitly asserts that a group is not a collection of arbitrary individuals.

Taken together, these characteristics provide essential attributes for a *group* in alignment with the interest of this dissertation research. It is therefore proposed that the term *group* refers to:

(a) a collection of two or more individuals;

(b) who are functionally related;

(c) who continuously engage in a direct (i.e., face-to-face) interaction(s); and

(d) who purposively perform towards a common objective(s);

Note that members of a group are "functionally" related for they are members of a specific organization which is supposed to last for a certain period of time – e.g., co-workers on a particular construction job site and for a specific project.

*<u>Question Two</u>: How does a construction work crew <u>function</u> from the perspective of a <u>group</u>?*

(2.2) Conceptual Reference Framework for a Group

In aforementioned diverse definitions for term *group* alongside with its characteristics, <u>individuals,</u> their <u>relationships</u>, their <u>interactions</u>, their <u>objectives</u>, etc. are [constitutional] elements of a group; and their varying properties exist at the time a group is formed. These elements can be referred to as *initial states* of a group (Hackman & Morris, 1975), and in part or as a whole facilitate *interaction* between its members.

While influenced by initial states, the interaction between group members imposes impact on initial states, and a cycle takes place. This cycle emerges to a product (e.g., an action; a completed activity; a decision; etc.) and represents *performance* of the group. While the performance is a variable depending on initial states and interactions, it itself will also affect both. These as a whole shape an interconnected system whose components are [classes of] variables which are ever-evolving, ever-influencing, interdependent, and interrelated. What adds more to this complexity is the simultaneous involvement of these variables in each cycle while a group functions. This “complex of mutually interacting components” (Arrow, McGrath, & Berdahl, 2000; Forsyth, 2014, p. 407) is conceptually presented in Figure 2.1.

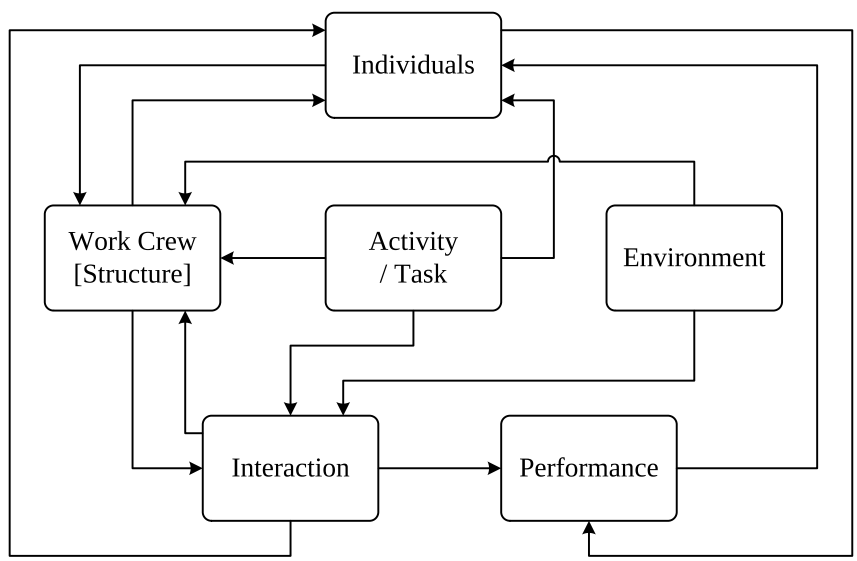


Figure 2.1 – Conceptual Presentation for Mutually Interacting Components of a Work Crew
Adapted from Source: (McGrath, 1964, p. 70)

In order to understand such a complex system and explore such an “ambiguous set of concepts” (McGrath, 1984, p. 12) it indeed is useful to create a model which serves as a guiding reference: a layout which depicts its various components; and a framework which represents underlying logics of this phenomena. A widely known reference framework for a group in Organizational Behavior literature is illustrated in Figure 2.2.

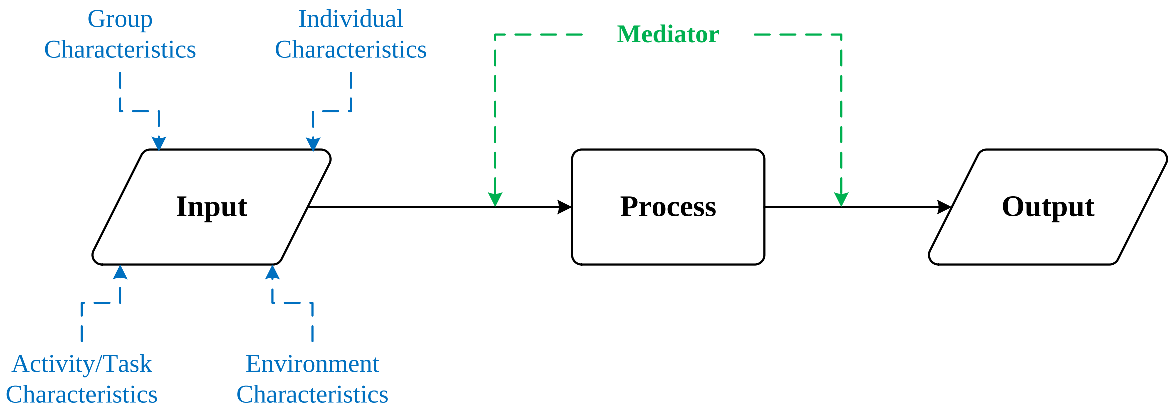


Figure 2.2 – Input-Process-Output (I-P-O) Conceptual Framework
Adapted from Source: (McGrath, 1964, p. 70; Hackman & Morris, 1975, p. 50; McGrath, 1984, p. 13) and (Stock, 2004, p. 278; Forsyth, 2014, p. 408)

In accordance with this conceptual model, a group may be represented as a linear, casual chain where:

(a) independent initial states are aggregated into *Input* – these factors feed into a group, and set the stage for members' collective work. Those independent initial states which indirectly affect the interrelated *Input-Process* cycle and either strengthens or weakens it are presented as *Mediators*;

(b) interdependent actions among members of the group are introduced as *Process* – it is technically what takes place in a group while members utilize resources and collectively perform an activity/a task to deliver a meaningful output; it is the relationship between *Input* and *Output*; and

(c) emergences from those two constructs are categorized in a dependent *Output* – that is a tangible result of a group's activities.

It is important to note that a group functions in manner much complicated than a simple cause-and-effect perspective may be able to capture. And for that matter, there are several critiques on this system. For example, it may not seem realistic to introduce components of such a complex, dynamic system as variables since what takes place in a group is mostly an emergent state(s); it is not sufficient enough to present a dynamic, complex system as a series of sequential status where a successor starts only when its predecessor completes its duties; there is an absolute need for a feedback cycle; etc. (Ilgen, Hollenback, Johnson, & Jundt, 2005; Forsyth, 2014).

*Question Three: What independent factors (i.e., initial states and mediators) do influence a construction work crew performance? And which of those influencing factors are critical on a work crew's performance in presence of a cue and a physical hint?*

The conceptual Input-Process-Output (I-P-O) framework of Figure 2.2 is to systematically present how a group functions: when at least two individuals form a group to deliver an output. It is expected that in this I-P-O paradigm inputs influence the outputs through process. In other words, the initial states of a group enable the group to process and deliver an output. Social Science literature focused on groups dynamics introduced different families of factors as such enablers.

## (2.3) Variables in a Group

The conceptual Input-Process-Output (I-P-O) framework of Figure 2.2 is to systematically present how a group functions: when at least two individuals form a group to deliver an output. It is expected that in this I-P-O paradigm inputs influence the outputs through process. In other words, the initial states of a group enable the group to process and deliver an output:

Morris (1966), Hackman (1968), and Hackman & Morris (1975) stated that characteristics of a task have a significant influence on group process. These authors found that type of a task contributes to group member involvement and offered a strong impact on group output; and that difficulty level of a task influenced the output of a group to a lesser degree.

Kent & McGrath (1969) found that task type and group gender composition were among strong determiners of a group performance characteristics.

Katzell et al. (1970) focused on a group process and its output; and identified three (3) input parameters leadership, difficulty of a task, and compatibility of group members to be of great importance. These authors argued that presence of leadership increased interaction among members of a group and decreased demands for information both of which improve output of group process. They also claimed that difficulty of a task contributes to agreement rate among group members which results in a better output. These authors also stated that compatibility of members improved productivity of group process and consequently impacted group output.

Stock (2004) focused on group processes; and found that leadership, characteristics of group members, and group interdependence were among input parameters which positively influenced collaboration, communication, and cooperation [i.e., process] in a group.

There are numerous initial states or inputs which have been introduced in social science literature and have been identified of important effects on a group process and, in turn, its output(s); and depending on focus of the investigation and what aspect(s) of a group was at stake in the study, some initial states were found to be more useful than others. It is therefore crucial to understand whether a relationship exists between <u>a particular input factor variable</u> and <u>an output of a specific</u>

situation. Arguably, input factors and initial states which were collected during previous researches may not be rightly applicable to a different study on group performance because each researcher collected data and introduced input factors in accord with her/his own specific purpose for the study, and consequently such data would need to be verified for the new research environment.

Deploying existing input factors in this investigation would have offered major challenges: (i) choosing from input factors for such widely studied phenomenon requires empirical verification – which would mean correlating output to input factors; or deriving input factors from output instead of input factors emerging outputs – and (ii) empirically verifying factors demand experimenting different what-if scenarios – neither of which would have been effective nor efficient; and could have potentially offered a false presentation of originality. These signify the importance of identifying influential input factors on a work crew interactions and consequently its outputs for a specific scenario – presence of cues and physical hints in case of this research dissertation.

*Question: How data can be collected about real-life experience of construction work crews?*

### *(2.3.1) Data Collection for Variables in a Group*

One source of data can be direct observation; however, it may not be efficient as it is not known when the instance under investigation will occur. Another source of data can be interviews with a group (e.g., a work crew) members and asking them about their experiences. Any commonly-known English dictionary defines '*Interview*' as '*a meeting of people face to face especially for consultation*' in its *verb* form and as '*question (someone) to discover their opinions or experience*' in its *noun* form. In academic research, however, interview is defined more specifically as 'verbal and body language' data gathered about a specific matter – e.g., another person's explanation of some behavior or action; a recollection (Yin, 2011). As Table 2.4 summarizes common strengths and weaknesses of an interview, it may be concluded that no source of data collection offers a set of complete advantages over any other one(s):

Table 2.4 – Strengths & Weaknesses in Sources of Evidence
Adapted from Case Study Research: Design & Methods (Yin, 1994, p. 80)

| **Source of Evidence** | **Strengths** | **Weaknesses** |
|---|---|---|
| *Interview* | Targeted: it focuses directly on the topic of investigation. | Biased induced due to poorly constructed questions may lead to errors. |
| | Insightful: it provides perceived causal inferences. | Response bias |
| | | Inaccuracies resulting from poor recall |
| | | Reflexivity: interviewee gives what interviewer wants to hear. |

*(2.3.2) Structured and Qualitative Interviews*

An interview can be conducted in two fashions (Yin, 2011): (i) a structured interview in which group (e.g., a work crew) members will be given a questionnaire or a list of specific questions. The questionnaire of a structured interview – also known as a survey – will force the participants to '*respond*' to a uniform set of questions. This will represent a *close-ended* discussion.

A structured interview is favorable in an investigation whose intent is to limit the responses to a set of pre-defined categories, and basically to ask a *close-ended* question (Murphy, 1980). In such a procedure, the pre-defined responses [for a question] are often offered for the purpose of corroboration. For the matter of such distinctive nature, structured interviews are rarely able to deal with the context of social life; and are the least common in evaluating ‘attitude, orientations, circumstances, and experiences’ (Babbie, 2010).

(ii) a qualitative interview in which the conversation and discussion will be based on a conceptual framework of the topic instead of a set of specific and uniform questions. In such an approach, an interviewee is encouraged to not only be a ‘*respondent*’ but also an ‘*informant*’ about the matter of investigation. In this *open-ended* question-and-answer the participant(s) is considered an ‘*informant*’ since the relative pieces of information will emerge from the discussion and in interviewees’ own words: how he/she lived a specific situation; and what her/his key take-aways were.

A qualitative interview may be considered an exploratory tool which is to depict a complex social world from a participant’s perspective; and to examine the reasons for complex events. It focuses on understanding the lived experience of other people and the meaning they make of that experience – that is, ‘*what*’ actually occurred, ‘*why*’ it happened, and ‘*how*’ the process was operated; the ‘*decision*’ that was made; and the ‘*impact*’ such an experience and decision poses (Murphy, 1980; Yin, 2011).

Section Two: Decision-Making in a Construction Crew

*Question Four: How does completeness of information and explicitness of an instruction, or its lack thereof, play a role in a construction project operation at its crew level?*

(2.4) Construction Operation and Variation in its Resources

The construction project performance literature has typically focused on productivity performance measures in a construction operation and reported many factors of crucial influence on productivity performance when they deviated from the plan; and because they deviated from what was expected from them. Whether due to a random and undesired event (e.g. equipment breakdown) or a non-random and controllable situation (e.g., unclear objectives) that deviation caused disruption, then resulted in work flow variation, and thus hindered productivity – (Koskela, 1992); (Halligan, Demsetz, & Brown, 1994); (Howell & Ballard, 1997); (Kaming, Olomolaiye, Holt, & Harris, 1997); (Chua, Kog, & Loh, 1999); (Radosavljević & Horner, 2002); (Thomas, Horman, de Souza, & Zavrski, 2002); (Liberda, Ruwanpura, & Jergeas, 2003); (Wambeke, Hsiang, & Liu, 2011); (Menches & Chen, 2014).

Variation has many dimensions (e.g., output; resource; time; etc.) and is a common phenomenon in almost any construction project – even those which are planned and managed well. In the Construction Industry, variation generally refers to deviation from an expectation – (Rilett, 1998); (Ballard & Howell, 1998; Howell, Ballard, Tommelein, & Koskela, 2004; Wambeke, Hsiang, & Liu, 2011); (Tommelein, Riley, & Howell, 1999); (Koskela, 1992); (Abdelhamid, 2011); (Wambeke, Hsiang, & Liu, 2011). In manufacturing, operation variation is defined as a random deviation, as a consequence of an event which is not under immediate control (Hopp & Spearman, 2008).

Lean Thinking in a broad scope, and Lean Production and Lean Construction as specific domains recognize the devastating influence of variation on work flow (Womack & Jones, 2003; Hopp & Spearman, 2008), and focus on reducing, if possible eliminating, variation in a construction operation work flow by ensuring that *<u>required resources</u>* for an activity are *<u>available at the right time</u>*. The Last Planner® System (LPS®) of Project Planning and Production Control is one of the Lean Construction techniques which emphasizes that forming a quality assignment for a work crew can reduce variation in work flow in an operation (Ballard & Howell, 1998; Ballard, 2000; Pikas, Sacks, & Priven, 2012).

The Last Planner® System (Ballard, 2000) suggested that a construction task be shaped based on four (4) quality criteria:

(i) Definition – an activity should be explicitly described so that beginning and end of the work can be identified; the appropriate amounts of resources can be considered; etc.

(ii) Soundness – an activity requires its pre-requisite activities/work to be completed; every required resource is available; etc.

(iii) Sequence – an activity should to be scheduled to start according to project delivery commitments; consistent with the logic of work execution; etc. and

(iv) Size – an activity should create only amount of work aligned with production capability of a work crew; achievable in plan available time; etc.

In manufacturing operations, Ronen (1992) referred to adequate and complete resources as the "Complete Kit" – a set of every requirement that an operation needs in order to be completed. The concept of Complete Kit suggests that an operation should not start until each and every requirement for its completion is available. The Last Planner® System soundness criteria can be inferred as an equivalent of the Complete Kit since it is to ensure that equipment, information, material, personnel, etc. necessary for an upcoming activity are available (Ballard & Howell, 1998; Koskela, 1999; Ballard, 2000; Koskela, 2004; Formoso, Sommer, Koskela, & Isatto, 2011).

### *(2.4.1) Incompleteness of Instruction and Implicitness of Information*

A construction project is a collection of activities which focus on a specific output (Koskela, 2000); a set of directive-driven activities which are often interdependent and interrelated and are designed to form certain physical outcome (Howell & Ballard, 1997; Ballard & Howell, 1998). An activity requires a set of resources to start; it consumes these resources in order to progress; and to produce a physical outcome at the right time. External conditions, directives and instructions, materials, personnel, etc. are among such resources.

A directive refers to "the information or instructions required for the construction crew to start the activity" – e.g., submittals; construction specifications; shop drawings; request-for-information (Abdelhamid, 2011). Prior research suggested that insufficient (i.e., variation in) "information" and implicit "instruction" adversely impact productivity performance of a construction project. For example, Ballard & Howell (1998), Chua et al. (1999), Dai et al. (2009), and Formoso et al. (2011) argued that errors in shop drawings, inadequacy of construction specifications, or inadequate information about project design, plans, and procedures created waste, resulted in rework, and ultimately hindered project productivity performance. Kaming et al. (1997), Koskela (2004), Lahouti & Abdelhamid (2012), and Arashpour et al. (2013) discussed that missing and/or unclear instruction brought about rework; that work redone was a waste and resulted in a longer execution time and cost. Ronen (1992), and Koskela (2004) referred to lack of information and need for more information as an Incomplete-Kit syndrome which may create rework and reduce productivity, and can eventually increase cost in an activity cycle and ultimately preclude completion of the planned activity (Handa & Rivers, 1983; Dozzi & Abourizk, 1993; Chua, Kog, & Loh, 1999).

Some other literature which recognized information and instruction as influential factors on construction project performance (e.g., cost; productivity; rework; safety; waste; etc.) are reported in Table 2.5.

Table 2.5 – Literatures Recognized *Incomplete Kit* Effect on Construction Project Performance

| **Factor** | **Reference** |
|---|---|
| Insufficient information | (Mohsini & Davidson, 1992) |
| Information [variation] | (Thomas & Sakarcan, 1994) |
| Poor instruction | (Kaming, Olomolaiye, Holt, & Harris, 1997) |
| Missing/unstable information and instruction | (Koskela, 2000; Koskela, 2004) |
| Information [variation] | (Thomas, Horman, de Souza, & Zavrski, 2002) |
| Non-availability of information | (Liberda, Ruwanpura, & Jergeas, 2003) |
| Shortage of information | (Shohet & Frydman, 2003) |
| Lack of information/inadequate instruction | (Dai, Goodrum, & Maloney, 2009) |
| Unavailable/unclear/incomplete information | (Formoso, Sommer, Koskela, & Isatto, 2011) |
| Lack of information | (Hamzeh, Morshed, Jalwan, & Saab, 2012) |
| Incomplete instruction/imperfect information | (Lahouti & Abdelhamid, 2012; Lahouti, 2013) |
| Lack of direction & information | (Menches & Chen, 2014) |

Starting an activity with incomplete resources is technically starting an activity with whatever is available and to improvise and to proceed with the means at hand. According to Ciborra (1999) improvisation is a natural human instinct and plays an "important role" when an element in a process falls short; it is a greatly contextual and absolutely situational action which cannot be planned before it actually happens. As cited by Cunha et al. (1999), improvisation is the ability to effectively adapt to the unforeseen; it is efficiently planning with resources to match the unexpected situation; and it is "making do with materials at hand" (p. 307). Cunha (2005) also defined improvisation as using whatever is readily available to make the best out of a situation when there is a problem; to make the best out of limited available resources in a moment when an unanticipated event happens. Hamzeh et al. (2012) defined improvisation as the ability to come up with a resolution for an unexpected issue and only utilizing resources that are available.

Koskela (2004) referred to this improvisation as a "making-do"; a situation in which a construction activity starts or continues with either unavailable or non-optimal and non-standard inputs. A making-do is indeed a response to the disruption which was caused by inadequacy of resources intended to accommodate and overcome the interruption induced by insufficiency of resources. Ronen (1992) argued that senses of obligation to improvise and to start an activity (or a portion of it) even with an incomplete kit – as if the activity will be completed earlier – were due to an urge of maximum resources utilization assuming it increases the overall productivity and "the fallacious notion that a worker should be busy all the time causes managers to have their people working using incomplete kits just so that they should not be idle" (p. 2459).

As Figure 2.3 conceptualized, the acts of improvisation and making-do are (examples of) how the construction work overcomes the disruption, and determines what-to do:


Figure 2.3 – Conceptual Reference Framework for Improvisation

For example, Formoso et al. (2011) introduced "lack of information" among the main causes of improvisation and making-do in a construction project operation; and stated that when a construction work crew faced an ambiguous situation, and when there was an uncertain and/or unexpected situation at the work face, the work crew had a tendency to employ any resources [e.g., information] which was readily available in its surrounding to reach the desired objectives.

Pikas et al. (2012) stated that when a planned construction activity was not sound with accord to the Last Planner® System (LPS®), it technically meant that the construction work crew was in need for more information. Therefore, the work crew evaluated its surroundings, gathered readily available information, and improvised and did make-do in order to fulfill its objective.

Hamzeh et al. (2012) discussed that when an activity could not start due to its unavailable prerequisite resources such as perfect information and a complete directive, the construction work crew would improvise and would utilize available information in order to execute that activity. The authors further argued that even employing the Last Planner® System as a Lean Construction tool might not eliminate improvisation, or interpretation, or making-do because focus of the LPS® would be on availability of “inputs” and “prerequisites”, it could not anticipate unexpected events – thus improvisation and making-do would help construction work crew to manage the situation.

Menches and Chen (2013), and Menches and Chen (2014) introduced “lack of information and direction” as an unexpected event which would disrupt construction project work flow; and as a trigger for improvisation and in-situ decision-making in a construction project operation. The researchers argued that “disruption” and “improvisational decision-making” were naturally built in any construction project because unexpectedness was an element of a construction project; and that because a construction project was a series of “plan-driven” operations, any disruption regardless of its type invited the work crew to improvise and to make a decision in order to overcome the situation and to resume execution of the plan.

Although recognizing that improvisation is itself a disruption, and that it can hinder the progress of an operation and/or a project, Eden et al. (2000) argued that improvisation must be done so the crew can "work-around" the disruption; otherwise further and perhaps other types of disruption would occur. For example, Pikas et al. (2012) reasonably claimed when a construction work crew decided to exercise making-do and continued the progress: (i) the flow of work might eventually stop because the work could not be completed which would add no value and could even cause further disruptions; (ii) the work would be done and progress would be made but under sub-optimal process which would deliver partial value and product might not be as optimal as expected and might require rework; and (iii) work could be completed under an optimal process and full value would be delivered.

*(2.4.2) Incompleteness/Implicitness of Information/Instruction and Cue Interpretation*

Interpretation of cues differs from the act of improvisation. With reference to the reviewed literature in previous section (2.4.1), improvisation in construction operation is to make the best out of incomplete, limited, available resources and to come up with a solution in the spur of the moment. Cue interpretation as conceptually illustrated in Figure 2.4 is, by contrast, to take a potentially *deceptive solution* that is *already present* at the work face, and fill the incomplete piece of information.

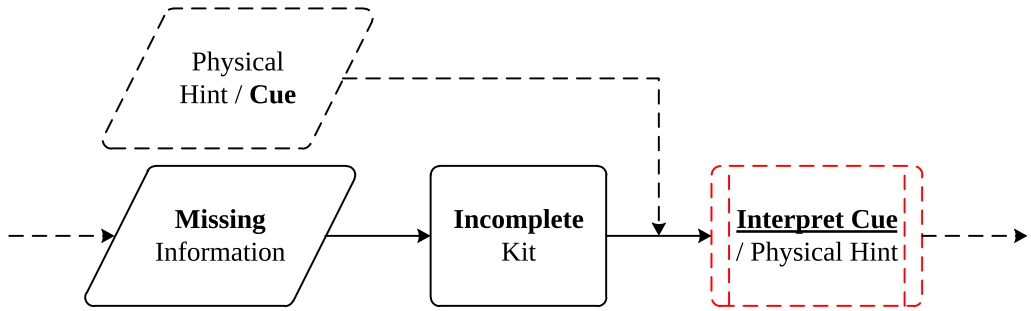


Figure 2.4 – Conceptual Reference Framework for Cue Interpretation

Cues are physical *hints*; they are *existing elements* of a construction job site – which can potentially misguide the work crew under specific circumstances; and they are NOT *generated solutions*. In other words, cues and physical hints appear to offer complementary information to the work crew members, yet fool their users. As Lahouti and Abdelhamid (2012), and Lahouti (2013) argued in order to restore the continuity of operation the construction work crew directs its efforts to deploy the most likely resolution by taking advantage of existing cues; and by interpreting the most relevant physical hints at work face surroundings to fill in for the missing information and instruction.

*Question: What is the gap in existing literatures which this research dissertation uncovers?*

The aforementioned Construction-Industry literatures addressed improvisation, and make-do as approaches work crews would take to deal with an *incomplete kit*. Employing existing cues and interpreting physical hints at the work face, however, was not discussed as other approaches for a construction work crew to autonomously deal with ambiguity of the *incomplete kit*. Neither was it considered that dynamics of work crews might influence improvisations, and make-do's as well their outputs. This research dissertation, thus, aims to fill in this gap by uncovering how interactions between members of a construction work crew correlates with usage and interpretation of cues when it faces incomplete directives at the work face.

With reference to Section (2.2) – Figure 2.1 and Figure 2.2 – the acts of improvising and making-do, gathering available pieces of information and interpreting of cues as outputs of work crew function may be well influenced by dynamics of their conductors – i.e., member of the work crew; yet no literature to the extent surveyed by this author – addressed such correlation.

The focus of discussion in this exploration is on the operation level of a construction project, and it is important to note that improvisation, making-do, and/or interpretation of a cue occur in all stages of a construction project (Formoso, Sommer, Koskela, & Isatto, 2011). For example, Hsu and Liu (2000) claimed that in the early design phase of a construction project, the design team would have to use a large amount of incomplete and imprecise pieces of information in its decision making process. And as such information could lead to different and perhaps conflicting improvisations and interpretations. Gomes et al. (2014) argued that the design team would spend much time to reason through different interpretations, to reach a common understanding of the matter, and to make-do.

*<u>Question Five</u>: How may correlation between <u>interpretation of a cue</u> and <u>interaction between construction work crew members</u> be investigated?*

As was discussed in Section (2.2) – and with reference to Figure 2.1 – a group is a complex, interdependent, and interrelated system with constituents which are heterogeneous entities carrying sets of unique characteristics and distinctive behaviors. Interactions between these constituents are dynamic processes which cannot be truly perceived in advance and before they occur – for it will be a product of several interactions within this complex system (Ahn, 2014). As pertains to research of this dissertation, for example, the influences that such interactions may impose on interpretation of cues; and that whether correlation exist between interpretation of physical hint and work crew interactions would not be apparent in advance as outputs of these ever-evolving interactions are emerging results, cannot be drawn from expectations, and ought to be observed per each scenario as a bottom-up process.

Observation is not always feasible. On the one hand, deliberately altering values and manipulating attributes of the process will be – if possible at all – a challenging task especially when it comes to observing human behavior. On the other hand, as Watkins et al. (2008) claimed, "direct observation" of events were often time consuming, and cost-inefficient; and as Sterman (1992, p. 4) added, in situations where such constraints did not apply people "even experts, have great difficulty inferring accurately the behavior of complex dynamic systems." After all, as Simon (1957, p. 198) argued, "the capacity of the human mind for formulation and solving complex problems is very small compared with the size of the problem whose solution is required for objectively rational behavior in the real world or even for a reasonable approximation of such objective rationality." Computer modeling and simulation approaches are helpful tools in overcoming some of these issues. Oreskes et al. (1994) argued that "the reason for modeling is a lack of full access, either in time or space, to the phenomena of interest".

## (2.5) Agent-based Modeling Simulation (ABMS)

Among computer simulation and modeling tools, Agent-based Modeling Simulation (ABMS) can represent dynamics of a construction project. Being a collection of interacting agents (Castiglione, 2006) in which each entity and its interactions may be directly presented (Ligmann-Zielinska, Agent-Based Models, 2010), an ABMS would be able to represent *complex behavior* and to reveal information about the *dynamics* of the system it represents (Bonabeau, 2002; Fortino & North, 2013).

An ABMS is constructed of two key components: a set of agents and an environment. Agents are heterogeneous entities which share a common environment, and autonomously interact with one another and also their underlying environment in order to represent a real-world system. Each agent owns unique characteristics, is bounded by a set of rules that govern its decision-making, and follows a specific set of actions each time it autonomously makes a decision (Bonabeau, 2002; Sawhney, Walsh, & Mulky, 2003; Ligmann-Zielinska, 2010; Du, 2012).

ABMS has become popular in Construction Industry research (Sawhney, Walsh, & Mulky, 2003; Desai & Abdelhamid, 2012; Du, 2012; Lahouti & Abdelhamid, 2012; Moore, 2013; Ahn, 2014) for perhaps advantages it offers over other computer modeling and simulation approaches. For example, Streman (1992), Banks et al. (2002), Bonabeau (2002), Srbljinovic & Skunca (2003), and Galán et al. (2009) discussed that ABMS captures emergent phenomena: an emergent phenomenon is an unpredictable and often ever-perpetuating resultant of a complex, dynamic system. The unique, nonlinear, and unpredictable interactions between members of a construction work crew that generate outputs (e.g., a decision) are instances of such phenomena.

ABMS provides a flexible framework for simulation: this research dissertation at large aimed exploring impacts of interactions between members of a construction work crew on its decision-making. This decision-making may be driven by a series of *what-if* scenarios in a crew operation. Simulating these *what-if*'s mandates deliberate alteration, and manipulation of key components of the ABMS by changing, for instance, population sizes for agents, adjusting rules for agents interactions, modifying agents attributes and characteristics, etc.

ABMS is explicit, and creates a natural description of a system – i.e., it represents a system from view-points of its constituents (i.e., bottom-up) instead of the processes that system follows (i.e., top-down). In example of a construction work crew, a more natural and realistic model defines operations of this work crew based on behaviors, and characteristics of its members and interactions between them (i.e., a bottom-up process), and therefore allows for outputs to emerge. In contract, a top-down model defines behaviors, and characteristics for members of this work crew based on their outputs.

In conclusion, ABMS seems an appropriate framework for modeling and a simulating method in understanding complex dynamics of construction projects, and specifically in crew operation level.

## (2.6) Summary

In this chapter exiting literature was surveyed with the purpose of answering research questions: First, the definitions for a group, its characteristics, and how it functions were reviewed. It was discussed that variety of factors and initial states would play roles in conceptual Input-Process-Output (I-P-O) framework of a group; that these factors would often be case-specific; and that deploying previously-identified factors in any other disciplines (e.g., the Construction Industry research) might not serve the purpose the investigation.

Second, literatures was reviewed to learn about studies on improvisation in construction project operations and in presence of imperfect information and incomplete instruction, and to solidify the topic of this dissertation research by determining the existing gap.

Last, agent-based modeling was discussed to as an appropriate simulation tool for Construction-Industry research for it is an explicit, flexible framework which can capture nonlinear, unpredictable, and emergent phenomena.

# (3) Research Method

This dissertation research, as stated in Section (1.3), postulates that interactions between members of a construction work crew influence the interpretation of cues on a construction project job site where directives and/or pieces of information are missing and/or incomplete. In order to investigate this problem and to verify its impacts, three objectives were proposed in Section (1.4). This Chapter outlines a plan to satisfy these objectives in Five (5) phases.

As summarized in Table 3.1, in *Phase One* existing relevant literatures were surveyed. Actual and real-life data was collected in *Phase Two* and its analyses were presented. In *Phase Three* a conceptual model of the Problem Statement was developed to provide a reference framework for *Phases Four* and *Five* in which a (computer) simulation was created, a series of experiments were designed, and corresponding outputs were analyzed.

Table 3.1 – Summary of Dissertation Research Plan

| **Phase** | **Task** | | **Product** |
|---|---|---|---|
| One: | Review & summarize literature | → | *Objectives One & Two* |
| Two: | Collect data & conduct statistical analyses | → | *Objective One* |
| Three: | Model a conceptual framework | → | *Objective Two* |
| Four: | Simulate the conceptual model | → | *Objective Three* |
| Five: | Conduct (simulation) experiment & analyze outputs | → | *Objective Three* |

## (3.1) Objective One – Research Approach

Stated in Section (1.4) and presented in Figure 3.1, the first objective of this dissertation research was developing a framework to identify factors which influence interaction among members of a construction work crew and its outputs.

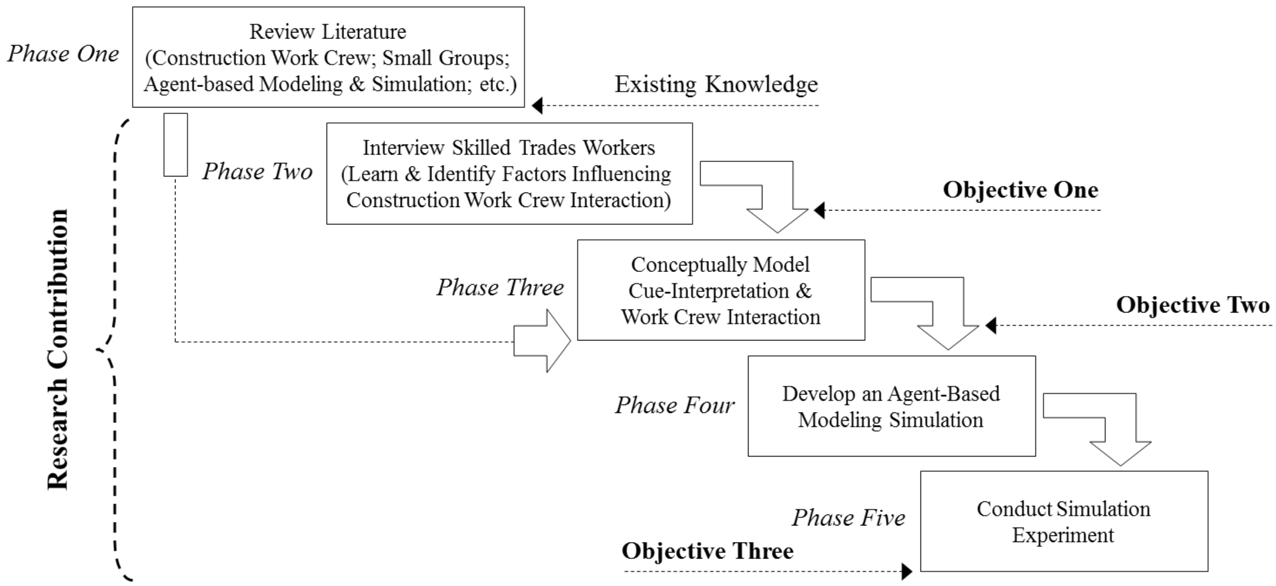


Figure 3.1 – Schematic Presentation of Dissertation Research Plan

A series of qualitative interviews approved by Michigan State University Institutional Research Board (IRB X15-377e) were conducted with a population of construction skilled trade workers who were selected based on their availability. Anonymous information about disciplines of their trades, and number of years they had been in a specific discipline was gathered, and the entire population was introduced to an identical real-life scenario. That scenario was then followed up by two (2) major questions of interests to this dissertation research in form of a non-structured, conversation-like discussion:

*<u>Question One</u>: How does a construction work crew act in/react to a situation where it is to make a decision in presence of cues, and physical hints? That is, what her/his most-likely, immediate action in such situation is.*

_Question Two_*: What are factors which will influence interaction among a construction work crew members when it conducts that situation in presence of cues and physical hints?*

The framework for qualitative interviews is presented in APPENDIX A. In their responses to these open-ended inquiries, each work crew member expressed her/his opinions and shared her/his experiences in similar situations. The contents of these responses were qualitatively analyzed and catch-phrases were identified with regards to each of follow-up questions. In an inductive research approach, then, these catch-phrases were clustered into mutually exclusive categories corresponding to *immediate actions* (i.e., Question One) and *influential factors* (i.e., Question Two). In the next step, contents of the interviews were statistically analyzed and frequencies of repetitions were determined for each category. Finally, the most-frequently repeated categories were identified to be critical factors and were considered in the conceptual model and – consequently – the computer simulation.

In short, Objective One aimed to: (a) understand heuristics of a construction work crew conduct when it encounters an ambiguous situation at the work face; and (b) identify factors influencing these heuristics.

## (3.2) Objective Two – Research Approach

The second objective in this dissertation research, as Figure 3.1 reports, was to develop a model which conceptually demonstrates interaction between members of a construction work crew when a crew was to interpret cues, and physical hints at the work face. In order to deliver this objective, first existing academic literature on *Small Groups, Group Dynamics,* and *Group Performance* were reviewed mainly to:

(i) define a group;

(ii) identify essential characteristics of a group;

(iii) learn about important factors which influence a group process and its outputs; and

(iv) understand how a group (e.g., a construction work crew) functions.

A construction work crew was examined from perspective of a group, and was evaluated whether it met a group's criteria.

The literature was also surveyed for a reference framework that conceptually depicted a group operate – so a general understanding of group's process was achieved and a framework could be developed accordingly to represent processes in a construction work crew and to conceptually model the interactions between its members.

Second, incorporating lessons learned from analyses of qualitative interviews contents (for *Question One* in Objective One) the reference framework of *Small Groups* proposed in academic literature was <u>adapted</u> to conceptually represent how a construction work crew would conduct the specific situation of interests in this dissertation research – i.e., interpretation of cues, and physical hints. This model was further developed to fulfill Objective Two when integrated with factors resulting from analyses of qualitative interviews contents for *Question Two* in Objective One.

(3.3) Objective Three – Research Approach

This research dissertation deployed an Agent-based Modeling Simulation (ABMS) in order to explore answers for the following (*Question Three*):

*Question Three: What correlation exists between influential factors and construction work crew performance in presence of cues and physical hints? Or between influential factors and construction work crew performance when its members are to interpret cues and physical hints – i.e., work crew's output?*

Three (3) major steps were designed and executed to achieve this objective.

*Step One* was to simulate actions of a construction work crew towards interpretation of cues and physical hints on a job site.

### *(3.3.1) Agent-based Model Simulation*

The conceptual model developed in Objective Two was simulated in programmable environment of *NetLogo*. As asserted in its *User Manual*, NetLogo is a "modeling environment for simulating natural and social phenomena" based on Java virtual machine. It is a 'simple-enough' yet 'advanced-enough' tool for simulating complex systems; and can "give instructions to hundreds or thousands of *agents* all operating independently. This makes it possible to explore the connection between the micro-level behavior of individuals and the macro-level patterns that emerge from their interaction" (Wilensky, 1999).

In order to simulate a *construction operation* in which a work *crew* exercises *cue-based decision-making*, an abstract model graphically presented in Figure 3.2 was designed:

Work Crew

In this maze, the blue circle symbolized a construction work crew of *n* members. This crew was to complete an activity.

Construction Operation

Each activity in a construction operations is a collection of several construction tasks. The white squares in this maze represented a set of tasks for completing the activity ‘reach the red square’ – the activity was to reach red square through the shortest path.

Cue and Physical Hints

Black squares represented a collection of obstacles to generate cues and physical hints. Combination of black and white squares created forks and cross-paths – which implied ‘*more than one shortest path*’. The blue circle was to decide on *correct* shortest path.

Decision-Making

The decision making was represented by the blue circle choosing one white square over the other one at a fork/cross-path.

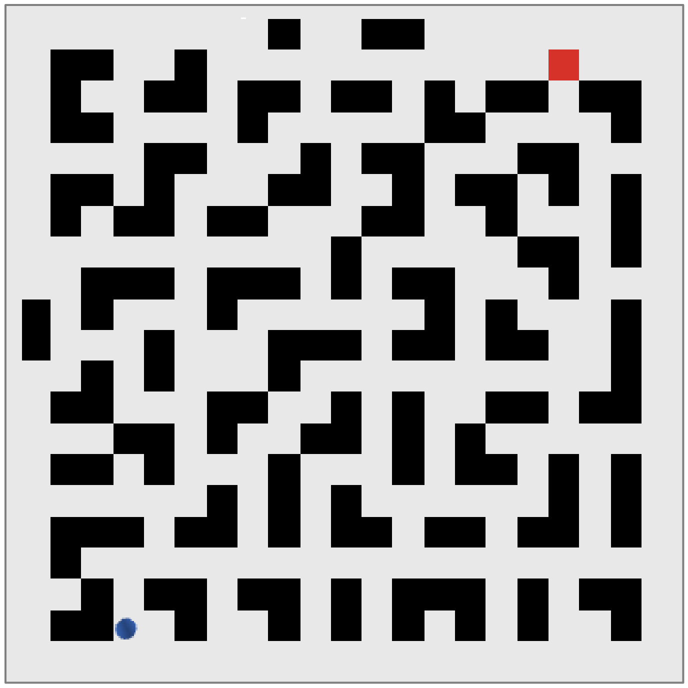

Figure 3.2 – Graphical Presentation of Developed ABMS

*Step Two* was to design an experiment to execute the ABM simulation. Software *SimLab* (version 2.2) was employed to generate a population of input values. *SimLab* uses Monte-Carlo methods to generate pseudorandom numbers based on a set of probability distributions functions. A uniform distribution of U (0,1) was defined for each input factor not only for the matter of simplicity but also because (specific) qualities of those factors were neither available nor within the investigation scope.

The '$A^*$ *Shortest Path*' algorithm was adapted to this ABMS and was employed by agents in search of the shortest path to red square neighbor.

*Step Three* was to execute the ABMS for the designed experiment for a reasonable number of cycles, and to analyze its outputs. A series of exploratory statistical analyses were conducted with software *R* (version 3.3.3); and sensitivity of this ABMS model to its inputs values was evaluated with software *SimLab* (version 2.2).

### *(3.3.2) Agent-based Model Analysis*

Exploratory Statistical Analysis

The statistical computations on ABMS outputs explored distributions of three (3) dependent variables with respects to independent input factors:

(i) Number of neighbors visited representing operation time;

(ii) Number of neighbors re-visited representing rework and waste; and

(iii) Number of neighbors dead-end representing need for more directives, and instructions.

Analysis Reference Value

To understand how each set of simulation outputs scattered with respect to input factors of interest, reference thresholds were introduced for values of input factors. As illustrated in Figure 3.3, these thresholds divided output values into four regions/quadrants.

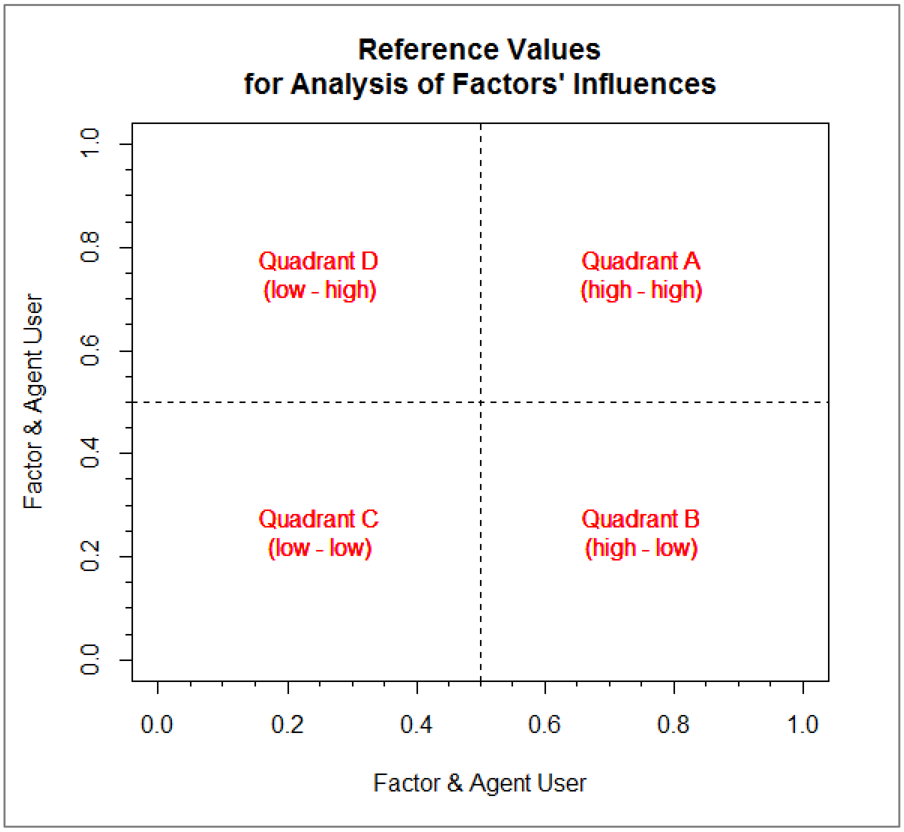


Figure 3.3 – Graphical Presentation for Analysis Reference Value

The output values (e.g., number of neighbors visited) which were populated in:

(i) *Quadrant A* were resulted from values *greater than 0.50* for each agent's input factors of interest (e.g., skillfulness);

(ii) *Quadrant B* were resulted from values *greater than 0.50* for input factors of interest for one agent, and values *lesser than 0.50* for input factors of interest for the other agent;

(iii) *Quadrant C* were resulted from values *lesser than 0.50* for each agent's input factors of interest; and

(iv) *Quadrant D* were resulted from values *lesser than 0.50* for input factors of interest for one agent, and values *greater than 0.50* for input factors of interest for the other agent.

Then, *Probability Density Functions* (PDF) were constructed for the model outputs to evaluate how (at large) the model behaved with respect to input factors values. Plotted for values in each quadrant of input factors of interest, PDF curves compared the likelihood that a particular output value would result from different values of that input factor. In other words, PDFs were constructed to explore how the ABMS responded to uncertainty of input factors.

Variance-based Sensitivity Analysis (SA)

In general term, *sensitivity analysis* is to prorate variations in model outputs to its difference inputs. *Variance-based measure* is among the known tools for sensitivity analysis in which variance of outputs are decomposed into model components. Saltelli, et al. (2008) favor~~ed~~ this technique for models of "unknown linearity, monotonicity, and additivity" (p. 37); and consider this method as model-independent, and capable to "capture the influence of the full range of variation of each input factor" (p. 158). In addition to those, Ligmann-Zielinska and Sun (2010) argue that because inputs in Monte-Carlo-based simulations (e.g., SimLab) are distributions of values, "it is only logical to utilize variance as a single-value measure that reflects the uncertainty of the outputs".

The mathematical representation of variance decomposition, adapted from Saltelli, et al. (2008), and Ligmann-Zielinska and Sun (2010), defines a global variance $\underline{V}$ to be the summation of local variances:

$$V = \left(\sum_{i}^{k} V_i\right) + \left(\sum_{i<j}^{k} V_{ij}\right) + \left(\sum_{i<j<m}^{k} V_{ijm}\right) \qquad \text{Equation 3.1}$$

where the first term represents the independent contribution of each *k* input factor in variations of outputs; the second, and the third terms express the variations of outputs due to interactions between *k* input factors. Sum of these terms accounts for total contribution of k input factors in variation of outputs – i.e., the left-hand side in Equation 3.1. The sensitivity indexes are calculated based on these variances, and as presented in the following equations (Saltelli, et al., 2008; Ligmann-Zielinska & Sun, 2010):

First-order Sensitivity Index ($S_i$) ........................................................................ Equation 3.2

$$\frac{V_i}{V} = \frac{V_{X_i}\left[E_{X_{-i}}(Y|X_i)\right]}{V(Y)}$$

Total-effect Sensitivity Index ($ST_i$) ................................................................... Equation 3.3

$$\frac{V(Y) - V_{X_{-i}}\left[E_{X_i}(Y|X_{-i})\right]}{V(Y)}$$

where *i* (1, 2, 3, … , k) represents each input.

Software SimLab was employed to calculate these indexes; and results of were interpreted with respect to scope of this research dissertation.

## (3.4) Summary

The research approaches discussed in this chapter illustrate how the three (3) major questions of this investigation were to address. These approaches comprised a plan of Five (5) Phases in which existing literatures were reviewed; real-life data was collected and analyzed; a conceptual and a computer simulation model were developed, experiments conducted, and conclusions made.

## (4) Data Collection and Analysis

## (4.1) Construction Work Crew and Group

As stated in Section (1.4) – Goal and Objectives – this dissertation research aims to better understand how interaction between construction work crew members may influence interpretation of cues on a construction job. Towards this understanding, it is natural to ask what happens in a work crew when there is a cue present, and how such dynamic influences interpretation of that physical hint. In order to approach these inquiries, the three critical research questions addressed in Chapter Two, were further explored.

*Question One: Does a construction work crew meet the required criteria to be addressed as a group?*

### *(4.1.1) Construction Work Crew*

The term *crew* [i.e., *work crew*] in commonly-known English dictionaries refers to *a collection of individuals* who *work together*. Merriam-Webster Collegiate Dictionary (2003), for example, addresses a work crew as a number of persons who “do a specific kind of work together”; who are involved in a “common activity”; who are associated in a “common interest”.

In Social Science literature this general and informal definition of work crew is converted to a “set of persons within an organization” who are “highly interdependent” (McGrath, 1984, p. 7); who perform “specialized” (Arrow, McGrath, & Berdahl, 2000) and “standardized, technical” (Forsyth, 2014, p. 405) tasks which demand “collective action” (Rousseau, Aubé, & Savoie, 2006, p. 540); and who pursue common “goals through coordinated, interdependent interaction” (Forsyth, 2014, p. 400).

In Construction Industry terminology, a work crew can refer to [almost always] a number of individuals trained in a specific trade discipline who work together on a construction job site for a specific period of time on a technical task that requires using equipment, tools, and/or technology (Spatz, 2000; Forsyth, 2014). For example, at the operation level of a construction project a steel-erector crew assembles a structural steel frame using a crane and wrenches; a sheet-metal crew installs Heating, Cooling, and Ventilation (HVAC) duct-work using a drill and screws; a masonry crew places bricks using a laser-level; a carpentry crew installs made-of-wood building materials using a nail/stable-gun. Thus, a *construction work crew* refers to *a few* skilled trade workers of same *discipline* who *collectively* perform a *particular* activity in a *construction project*.

Does such *collective behavior* classify a work crew as a *group*? In other words, does a *construction work crew* have the required criteria and/or qualifications to be addressed a *group*? In order to investigate this classification, a *group* will be studied in its professional/scientific terminology.

It should be noted that in academic literature a '*group*' is sometimes defined differently from a '*team*'; that a team is a group yet a group does not always satisfy every qualification of a team (Katzenbach & Smith, 1993; Stock, 2004; Forsyth, 2014). In this research dissertation, nevertheless, these two terms are considered interchangeable.

### *(4.1.2) Construction Work Crew as a Group*

The comprehensive definition for a *construction work crew* which was provided in Section (4.1.1) indeed captures at the least three (3) central features and key characteristics which are common among different definition of a *group*. Specifically, those are:

(a) size – a minimum of two (2) skilled trade workers;

(b) commonality – a specific construction activity/task which has be completed; and

(c) interaction – a continuous and collective work style to deliver a product.

Such qualification enabled the researcher to apply the abstract Input-Process-Output (I-P-O) model by which social science addresses small group dynamics and its interactions to construction work crew.

*Question Two: How does a construction work crew function from the perspective of a group?*

(4.2) Conceptual Reference Model for Dissertation Research

As defined in Section (4.1.1), a construction work crew is a number of individuals trained in a specific trade discipline who work together on a construction job site for a specific period of time on a technical task that requires using equipment, tools, and/or technology.

In such a setting, individuals may be of different ages, genders, and races; each may have diverse characteristics and personalities; and every one may have varying expertise, levels of knowledge, sets of skills, years of experience, etc.

The group which these trained individuals of a specific discipline form in a construction project have to follow certain norms and regulations enforced by that group, pursue directions provided by their superiors; as members of a crew, every one may have to assume responsibilities; members may have to work collectively and interact with other (new) members, and construct some kinds of relationships – unless there was a past history such as friendship, work experience, etc.

The technical activity which this work crew has to perform may be of a special type, a certain level of complexity and difficulty, and it may require specific knowledge, skills, training, etc.

The construction <u>job site</u> where the crew is expected to work may also have some characteristics. For example, it may be located in an extreme environmental condition; it may be in a very high-security location, a heavy-traffic, a unique surrounding neighborhood, etc.

*<u>Question Three</u>: What <u>independent factors</u> (i.e., initial states and mediators) do <u>influence</u> a construction work crew <u>performance</u>? And which of those influencing variables are <u>critical</u> on a work crew's performance in presence of <u>cues and physical hints</u>?*

Four types of input factors in Figure 4.1 likely trigger members of a construction work crew to interact with one another and render a decision. Therefore, *process* may be considered as a vehicle which carries initial states of a group to impact its performance outputs.

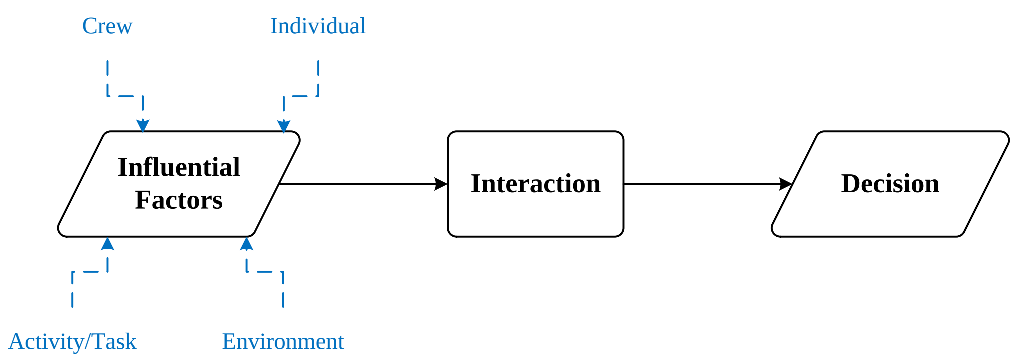


Figure 4.1 – Construction Work Crew Input-Process-Output (I-P-O) Conceptual Framework
Adapted from Source: (McGrath, 1964, p. 70; Hackman & Morris, 1975, p. 50; McGrath, 1984, p. 13) and (Stock, 2004, p. 278; Forsyth, 2014, p. 408)

As stated previously, and also in Chapter Three, in order to identify relevant initial states (i.e., independent input variables) of a construction work crew I-P-O, a population of skilled trade workers were interviewed.

## (4.3) Research Findings: Analysis and Discussion

Construction work crews hold major roles in construction project activities and operations, and offer significant influence on operations performance and outputs. It is thus important that work crew members are involved in identifying initial states which significantly influence a construction work crew. Dai et al. (2009) claimed that construction work crews would rarely be invited to take parts in such investigations perhaps because: (i) they would be taken away from work face and would not be working on an activity; and/or (ii) it would be a matter of authority and would seem to be the responsibility of a project manager.

In order to understand the heuristic of construction work crew decision-making in an ambiguous situation, and to learn about factors which influence such heuristic in presence of cues and physical hints, a population of hundred and seventy six (176) construction skilled trade workers were qualitatively interviewed. Interviewees were selected based on availability, and their willingness for participation. The characteristics of interviewee population are reported in Table 4.1.

Table 4.1 – Population Characteristics of Interviewee Construction Crews

| **Skilled Trade** | **Sample Size** Owner Self-Performing | Specialty, Sub-Contractor | |
|---|---|---|---|
| Electrician | 2 | 47 | An Average of **17 Years** Experience |
| Rough Carpenter | 5 | 33 | |
| Trim Carpenter | 7 | 43 | |
| Tin Knocker | | 39 | |
| **Population Size** | **14** (8%) | **162** (92%) | |

The interviews were conducted one-on-one at construction job sites, and each lasted for an average of thirty minutes. Each interviewee was asked to refer to following scenario that he or she might have encountered throughout her or his career as a construction skilled trade worker:

> *When you arrived on the job site, you realized that the situation did not match the instructions (e.g., construction drawing; verbal request; work-order; etc.) originally received; and you needed to acquire more information or informative instruction in order to complete your activity/task. In the meantime, there was a readily-available physical cue at the work face which might have – rightly or wrongly – filled in for the missing pieces of information*.

Two discussion topics were followed. In the first follow-up discussion each interviewee was asked to describe her or his most-likely, immediate action in such a situation considering that he or she would often work in a crew. Notes were taken from discussions and responses each skilled trade worker provided.

From the contents analyses of interviewees responses to this follow-up question, one hundred and eighty three (183) '*catch-phrases*' were extracted, which were then clustered into three (3) mutually exclusive actions categories presented in Table 4.2.

Table 4.2 – Work Crews Most-Likely Immediate Actions in an Ambiguous Situation (from Contents Analyses of Qualitative Interviews)

| **Immediate Action** | **Catch-phrase in Qualitative Interview** |
|---|---|
| Autonomous Problem-Solving | e.g., discuss with team member; review drawing/scope of work/work order; assess the situation; remembering similar past mistakes |
| Contact Customer | e.g., communicate with customer; learn what customer needs |
| Contact Supervisor | e.g., ask project manager for instruction; discuss with supervisor |

Autonomous Problem-Solving

Analyses of interviews contents revealed that construction work crew members referred to '*Autonomous Problem-Solving*' – that is, he or she would try to resolve the issue in crew and/or between crews – one hundred and twenty seven (127) times; what made a frequency of almost sixty nine percent (69%) of catch-phrases – as summarized in Figure 4.2.

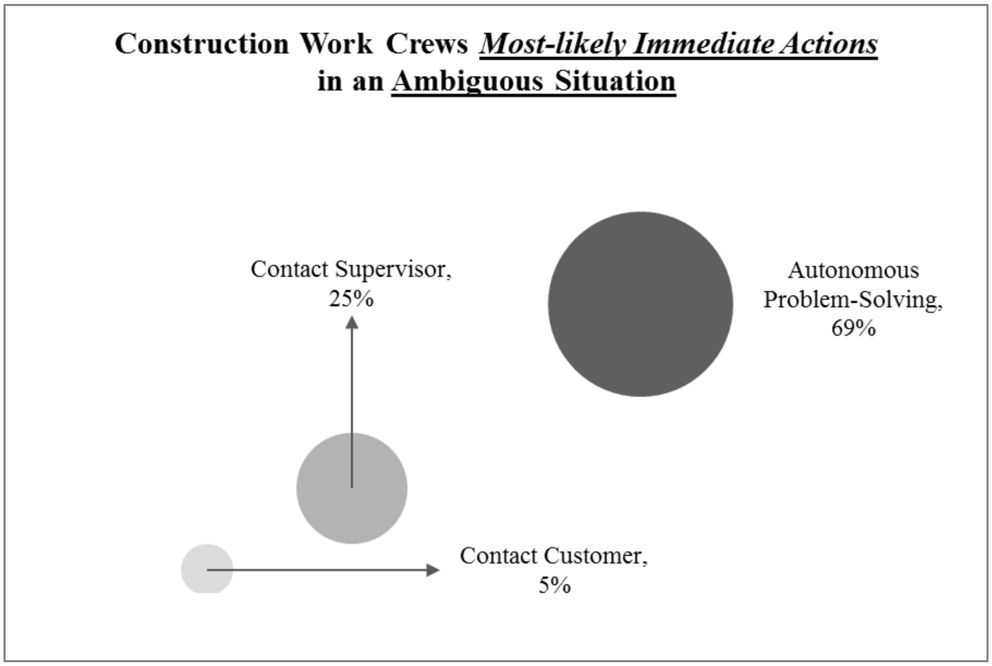


Figure 4.2 – Frequency Analyses of Work Crews Immediate Actions

Skilled trade interviewees expressed that:

(i) they had knowledge of current building codes and were aware of construction regulations applicable to a situation;

(ii) that often in each circumstance things could be constructed in a certain way and/or only particular things could be constructed; and

(iii) that within the crew they had a great number of years of experience, and a rich combination of expertise available to them.

Therefore they were eager to evaluate the situation with respect to scope of work, to re-study and review the construction documents, and to discuss the issue with their crew-mate(s) in order to interpret the circumstance, and to make a sound decision.

Contact Supervisor

Skilled trade interviewees referred to '*Contact Supervisor*' as their immediate response forty six (46) times – a frequency of 25% in extracted catch-phrases. These work crew members mentioned that they wished to respect the hierarchy of responsibilities, and to follow the lead of their superiors – even though they themselves knew what needed to be done, these skilled trade workers preferred to receive further instructions from their supervisors.

Contact Customer

'*Contact Customer*' was least frequent catch-phrase in the interviews contents. Skilled trade interviewees mentioned ten (10) times – a frequency of 5% – that "the customer was to pay for the work" and that "it was important to involve the customer in decision making". Therefore they contacted the customer prior to taking any action. These crew members stated they communicated with the customers to learn about their desired work outputs, and to share with and/or teach them about the situation.

*(4.3.1) Autonomous Problem-Solving*

As shown in Figure 4.2, the majority of interviews content [for the first follow-up discussion] fitted in the category of '*Autonomous Problem-Solving*', and supported the Problem Statement asserted in Section (1.3) – that is, when a construction work crew faces an ambiguous situation at their work face, the work crew tends to rely on readily available hints in its surroundings in order to make a decision about proceeding. On that basis, and also findings presented by Lahouti & Abdelhamid (2012), and Lahouti (2013) a conceptual framework for such a process was developed as illustrated in Figure 4.3.

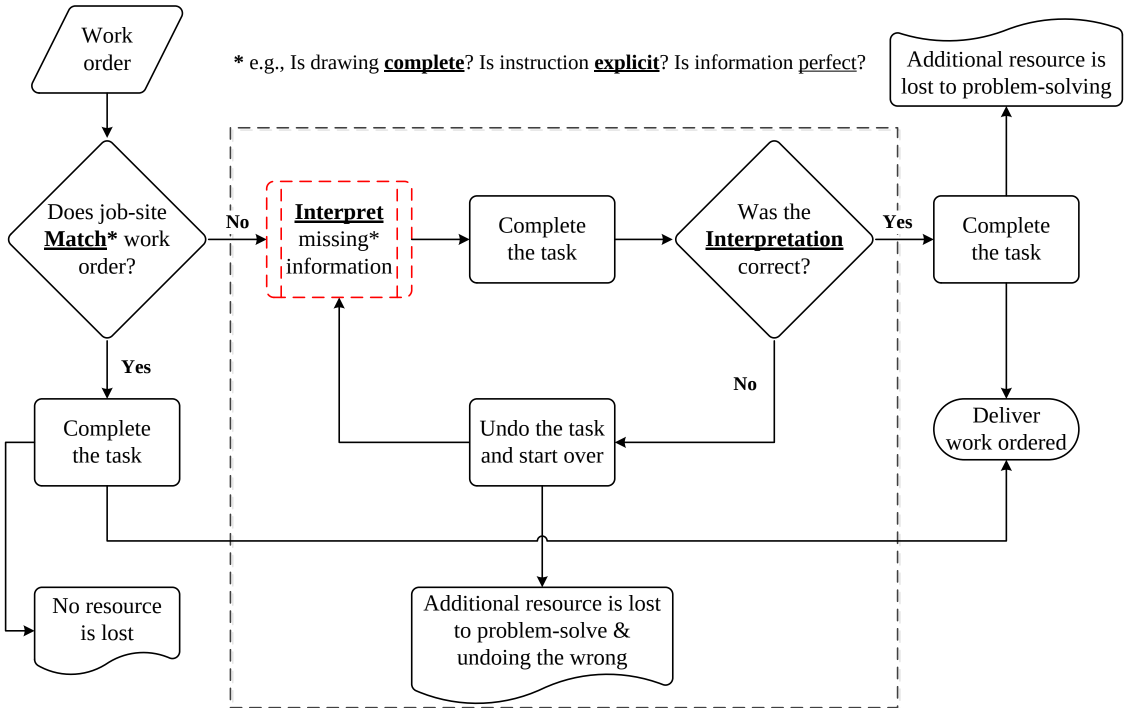


Figure 4.3 – Conceptual Framework for Work Crews Autonomous Problem-Solving

The autonomous problem-solving framework of Figure 4.3 demonstrates that when a construction work crew arrives at a job site, and finds its workface different from provided work-directives, and that based on construction documents (e.g., shop drawings; work-orders; etc.) the work face condition does not match with its expectation, then – according to this investigation – 69% of actions that the work crew immediately takes on to complete its assigned work focus on finding the missing information, interpreting present ambiguity, and decision-making by relying on surroundings cues and hints which are readily available. When the decision leads to incorrect and/or undesired outputs (i.e., a waste) the work crew has to undo its work, and to find additional information from other sources, and then correctly re-complete its work. The dotted rectangle in color 'black' in Figure 4.3 identifies the cue-interpretation loop.

Heuristics of the autonomous problem-solving were concluded from contents analyses of qualitative interviews with construction work crews and are summarized in Figure 4.4 – where action “Discuss with other crew member(s)” was mentioned one hundred and seven (107) times (i.e., a frequency of 84 percent).

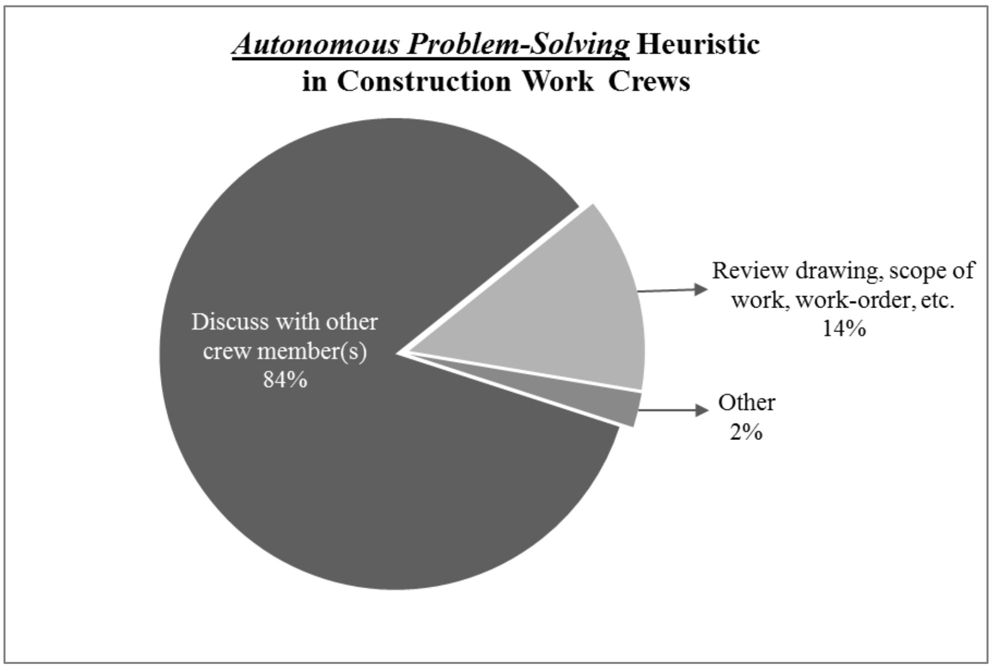


Figure 4.4 – Frequency Analyses of Work Crews Autonomous Problem-Solving Heuristics

This frequency is also in agreement with the Problem Statement of this research dissertation stated in Section (1.3) that interaction between members of a construction work crew is attribute to its decision-making. Application of Input-Process-Output reference framework of Figure 4.1 to the autonomous problem-solving process map conceptually illustrated in Figure 4.3 may define the heuristics of cue-interpretation within the scope of this investigation.

As conceptually presented in Figure 4.5, *missing information* about activities/tasks forces a work crew to *interpret missing information*, which in turn demands *interactions* between crew members. The quality of these interactions is functions of *characteristics* of each member – the input factor concerned in this research dissertation. As a result of these interactions, physical hints at the work face are *interpreted* and accordingly a *decision* will be rendered to complete the activity/task.

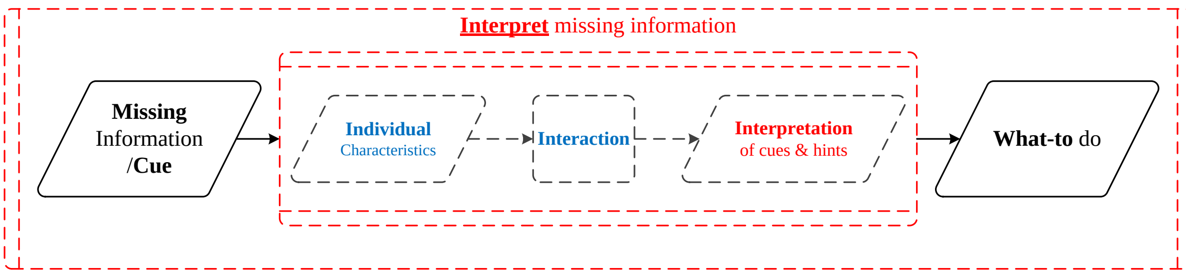


Figure 4.5 – Conceptual Heuristic of Cue Interpretation in Construction Work Crews

The second follow-up discussion focused on factors which were influential on interactions between work crew members. Each interviewee was asked to discuss the factors (e.g., individual; environmental; etc.) which in her or his opinion were the most important in the process of making a decision as a work crew. From the contents analyses of these unstructured, and open discussions two thousand and seventy (2070) catch-phrases were extracted, and clustered into fourteen (14) descriptive factors. It should be noted that these factors were described in such a fashion to inductively represent catch-phrases, and to describe implied contents of interviews. Table 4.3 reports these influential factors alongside their repetition counts.

Table 4.3 – Influencing Factors on Construction Work Crews Interactions
(from Content Analysis of Qualitative Interview)

| **Influential Factor** | **Count** | **Catch-phrase in Qualitative Interview** |
|---|---|---|
| Collaboration | 17 | e.g., willingness to work as/in a team |
| Common Sense | 116 | e.g., common sense |
| Communication | 159 | e.g., communication; listening; sharing ideas |
| Complexity of Task | 87 | e.g., difficulty of execution; whether there is a need for architectural/structural design |
| Confidence and Trust | 298 | e.g., confidence in team member; past experience/history with team member; trusting team member |
| Cost and Efficiency | 181 | e.g., being more productive; completing a task cheaper/easier/faster |
| Customer Satisfaction | 36 | e.g., what customer interest/need/preference/satisfaction is |
| Feasibility of Solution | 14 | e.g., code compliance; owner specifications/standards; what best interest/option/service/value [for customer] is |
| Knowledge and Skills | 457 | e.g., team member's ability/capability; team member's craftsmanship, experience, skill, and training |
| Morale and Personality | 214 | e.g., how team member approaches with a suggestion; team member's attitude; team member's honesty |
| Mutual Respect | 156 | e.g., respect team member's opinion/responsibility; respect team relationship |
| Open-mindedness | 266 | e.g., accepting/considering team member's solution/suggestion; being open-minded; considering that there may be a better/different way of doing things |
| Quality of Product | 39 | e.g., aesthetic considerations; ease of future maintenance |
| Work Style | 30 | e.g., work style |

Knowledge and Skills

As presented in the histogram of Figure 4.6, the factor *Knowledge and Skills* of a work crew member was acknowledged the most frequently by interviewees. The construction work crew members stated that degree of experience, diversity in expertise and specialties, capabilities, level of craftsmanship, and types of trainings were the most impactful factors on their within- and between- crews interactions and processes of rendering a decision on what-to do. This conclusion from the interviews contents is in tune with Hamzeh et al., (2012) claim that knowledge, skills, and abilities of a construction work crew member (i.e., he or she who improvises) influence the improvisation outcome. The existing literature on *Small Groups* and their *Dynamics* also recognize a relationship between knowledge, skills, and abilities of group members and the overall performance of group and its outcome (Jones, 1974; Bennis & Biederman, 1997; Forsyth, 2014).

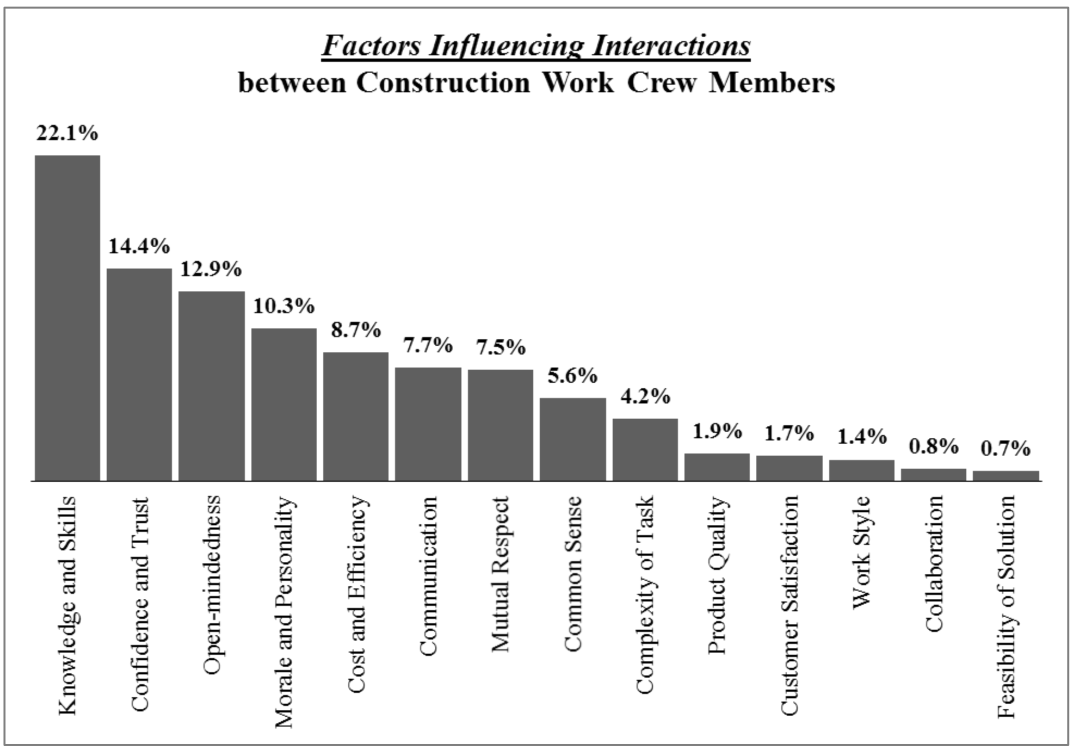


Figure 4.6 – Frequency Analyses of Influencing Factors on Work Crew Members Interactions

<u>Confidence and Trust</u>

*Confidence and Trust* was the second influencing factor to which construction work crew members referred the most frequently. The interviewees recognized this factor from two different aspects of: (a) morality – this is, whether their crew-mate could be trusted as a human being, whether he or she was trustworthy, and (b) professionalism – that is, whether their crew-mate made a suggestion to only complete her or his assignment; or he or she offered a well-thought, value-adding decision. The interviewees acknowledged that level of *Confidence and Trust* in their crew-mates rooted in the past experiences – if any – they had with her or him where they witnessed her or his approaches, decisions, and actions, whether he or she presented a bad judgment, and whether he or she was ignorant, and/or oblivious.

Open-mindedness

The third most-frequently recognized influential factor by interviewees was *Open-mindedness*. Based on their years of experiences on construction job sites, the work crew members asserted that it was important to accept that their crew-mates had different opinions; and that he or she had a different approach in problem-solving. They interviewees concluded that *Open-mindedness* of their crew-mates and that he or she would even consider other's suggestions/solutions were often crucial in the crew performance.

Moral and Personality

*Moral and Personality* of the construction work crew members was the fourth most-frequently mentioned factor. The interviewees stated that their crew-mates' attitudes, how personable he or she was, and how he or she reached out to the crew as a unit with a suggestion affected the dynamics of interactions between them, and how the crew shaped its decisions.

## (4.4) Statistical Analysis

As reported in Table 4.1, a small portion of interviewee population – i.e., a sample size of fourteen (14) which made almost 8% of entire population – was represented by *Owner Self-Performing* work crews of a higher-education institution; and the rest of population was represented by *Specialty, Sub-Contractor* work crews. The most prominent difference between these two work-crew types was their *structures* – or rather, as addressed in Section (4.2) and illustrated in Figure 4.1, *characteristics* of the crews. Although these characteristics were largely determined by common, standard regulations of construction work crews, owner self-performing crews exercised a set of uncommon norms. For example, while the specialty sub-contractors crews represented common characteristics of typical construction work crews – as such was, hierarchy of responsibilities and roles within a work crew (foremen, journeyman, etc.), temporary professional partnerships of crews on construction job sites, or competition between work crews of similar disciplines, etc., in the owner self-performing work:

(i) members of each trade were expected to assume equal roles within their crews;

(ii) work crews were professional partners in almost every job site;

(iii) *value* was not solely in completing assignments as work crews were owner's representatives – hence no sense of competition; etc.

Analyses of interviews contents when controlled for influential factors revealed that trades of diverse disciplines and crews of different structures differently weighted (i.e., mentioned with different frequencies) the impact of each (influential) factor. Such comparison however is not to imply that different construction skilled trades and/or work crews disregarded the influence of one factor over another. Rather, it is to demonstrate variation for intensity of impact that different skilled trades and/or work crew types believed a factor would impose on their interactions with other crew members; that influential factors were possibility dependents of the characteristics of work crews, their trade disciplines, and/or their activities/tasks. Statistical analyses were conducted in order to evaluate the differences between these frequencies.

### *(4.4.1) Examination for Association*

Table 4.4 summarizes the frequencies of influential factors with respect to each trade's discipline. To determine whether differences between these frequencies suggest any association with trade's disciplines, *Chi-Squared* Test of Independence was conducted. In other words, *Chi-Squared Test* was to determine whether the proportion of frequencies for factor Knowledge and Skill, for example, was significantly different between electricians, carpenters, and tin-knockers.

Table 4.4 – Influencing Factors on Construction Work Crews Interactions with Respect to Trade

| **Influential Factors** | **Electrician** | **Rough Carpenter** | **Trim Carpenter** | **Tin Knocker** | **Total** (Table 4.3) |
|---:|:---:|:---:|:---:|:---:|:---:|
| Collaboration | 4 | 6 | 4 | 3 | **17** |
| Common Sense | 29 | 29 | 29 | 29 | **116** |
| Communication | 44 | 30 | 50 | 35 | **159** |
| Complexity of Task | 24 | 23 | 18 | 22 | **87** |
| Confidence and Trust | 87 | 61 | 81 | 69 | **298** |
| Cost and Efficiency | 53 | 36 | 49 | 43 | **181** |
| Customer Satisfaction | 6 | 8 | 16 | 6 | **36** |
| Feasibility of Solution | 4 | 2 | 5 | 3 | **14** |
| Knowledge and Skills | 130 | 94 | 124 | 109 | **457** |
| Morale and Personality | 62 | 44 | 58 | 50 | **214** |
| Mutual Respect | 46 | 33 | 40 | 37 | **156** |
| Open-mindedness | 72 | 64 | 72 | 58 | **266** |
| Product Quality | 8 | 9 | 13 | 9 | **39** |
| Work Style | 8 | 6 | 10 | 6 | **30** |

The *R Statistical Computing Platform* returned a relatively small *Chi-Squared* of **18.852**, and a *p-value* of **0.9973** ($\alpha = 0.05$). The hypothesis that influential factors were identified ***independent*** of trade's disciplines therefore cannot be rejected. In other words, these values suggest that frequency of identifying a factor influential appeared to be statistically unassociated with the trade's discipline; and that frequencies of identifying a factor as influential were similar between different trade's disciplines.

Similar hypothesis that identified influential factors were also ***independent*** of crew types was tested with respect to interviews contents summarized in Table 4.5. The *R Statistical Computing Platform* returned a *Chi-Squared* value of **171.6** with the probability of **2.2e-16** ($\alpha = 0.05$) – both of which indicate a statistically significant difference in frequencies of identifying influential factors with respect to crew types.

Table 4.5 – Influencing Factors on Construction Work Crews Interactions with Respect to Crew Type

| **Influential Factors** | **Owner Self-Performing** | **Specialty Sub-Contractor** | **Total** (Table 4.3) |
|---|---|---|---|
| Collaboration | 6 | 11 | **17** |
| Common Sense | 3 | 113 | **116** |
| Communication | 12 | 147 | **159** |
| Complexity of Task | 5 | 82 | **87** |
| Confidence and Trust | 7 | 291 | **298** |
| Cost and Efficiency | 5 | 176 | **181** |
| Customer Satisfaction | 13 | 23 | **36** |
| Feasibility of Solution | 6 | 8 | **14** |
| Knowledge and Skills | 16 | 441 | **457** |
| Morale and Personality | 5 | 209 | **214** |
| Mutual Respect | 5 | 151 | **156** |
| Open-mindedness | 21 | 245 | **266** |
| Product Quality | 8 | 31 | **39** |
| Work Style | 3 | 27 | **30** |

In order to evaluate how significant these differences are, Fisher's Exact Test for Statistical Significance was conducted in *R Statistical Computing Platform*.

### *(4.4.2) Analysis of Differences*

In order to evaluate whether these differences in frequencies were of any significant importance, Fisher's Exact Test for Statistical Significance was conducted in R Statistical Computing Platform.

Owner Self-Performing Work Crews

While bar chart of Figure 4.6 represented each factors in relation with the entire population of interviewees, Figure 4.7 categorized factors on which the owner self-performing work crews emphasized with greater frequency – that is: *Customer Satisfaction*, *Product Quality*, *Feasibility of Solution*, and *Collaboration* as those strongly influential on their interactions.

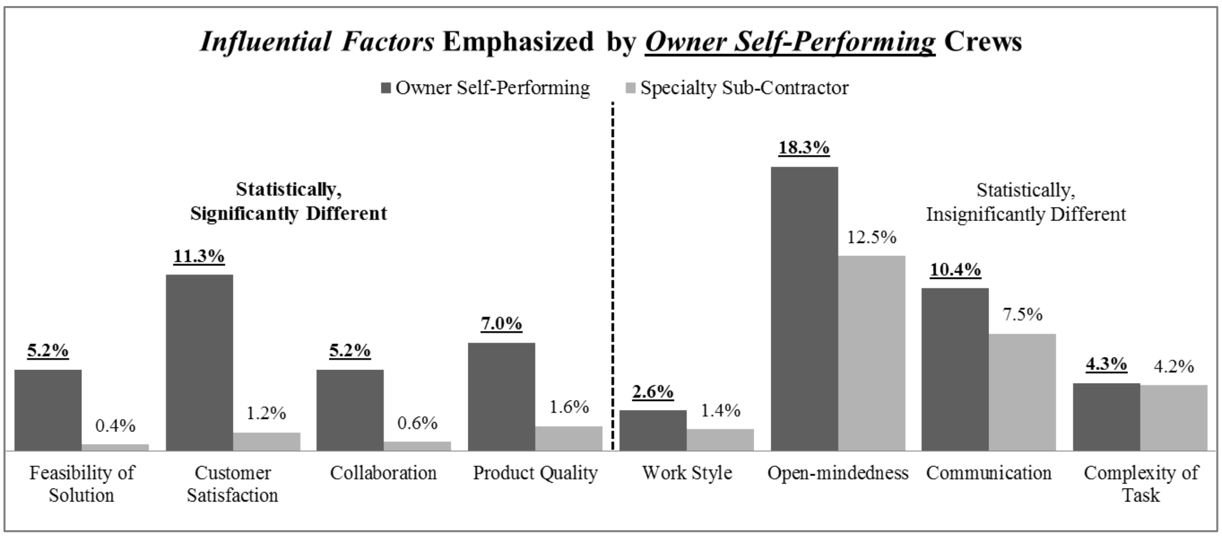


Figure 4.7 – Comparison of Influential Factors with Greater Frequencies for Owner Self-performing Work Crew

The results of Fisher's Exact Test for statistical significance – reported in Table 4.6 – revealed that odds of the self-performing work crews referring to factor *Feasibility of Solution* was thirteen (13) times greater than that of the specialty sub-contractor crews. Similarly, these odds for factors *Customer Satisfaction*, *Collaboration*, and *Product Quality* were respectively eleven (11), ten (10), and five (5) times greater for the owner self-performing work crews. Although factors *Open-mindedness*, *Communication*, *Complexity of Task*, and *Work Style* were also acknowledged by owner self-performing work crews more frequently, the Fisher's Exact Test reported that their differences were not *statistically* significant – that is, both crew types emphasized these factors as strongly.

Table 4.6 – Fisher's Exact Statistical Significance Test Result: Influential Factors of Greater Frequencies for Self-Performing Work Crews

| **Influential Factor** | **Odds Ratio** | **p-Value** | |
|---|---|---|---|
| Feasibility of Solution | 13 | 0.00005 | Statistically Significant |
| Customer Satisfaction | 11 | 0.00000 | Statistically Significant |
| Collaboration | 10 | 0.00019 | Statistically Significant |
| Product Quality | 5 | 0.00103 | Statistically Significant |
| Work Style | 2 | 0.23060 | Not Statistically Significant |
| Open-mindedness | 2 | 0.08438 | Not Statistically Significant |
| Communication | 1 | 0.27630 | Not Statistically Significant |
| Complexity of Task | 1 | 0.81280 | Not Statistically Significant |

A possible explanation for statistically-significant differences can be that these work crews did not consider their customers the only owners, and solely the entities which pay for the work; instead they understood that they themselves were representatives for the owner (i.e., in-house crews), assumed owner roles in delivering the desirable end products, and paid more attention to what the customer wished to receive. The core activities of these owner self-performing crews were focused on alteration and improvement of facilities which aged for one year to several decades. Taking the time to discuss things that could be done in presence of *existing conditions*; and to collaboratively determine those which provided the best value(s) in the interest of the owner, while taking into account the maintenance-ability of end products, and also the ease of future alteration and/or improvement work promised these work crews the delivery of high-quality end products. Given these characteristics of activities, these crews believed that feasibility of suggested solutions contributed much in quality of their deliverables. The senses of ownership can also explain the different immediate actions that these work crews emphasized in comparison with specialty sub-contractor crews.

An important remark in regards with factor *Complexity of Task* is that work crew members addressed this factor in two different contexts: (a) they counted complicated activities/tasks more ambiguous and therefore influential on their interactions with crew-mates for it did invite more discussions, and exchanges of knowledge and skills; and (b) every interviewee stated that her or his first action when faced with an ambiguous situation was dependent on its complexity. That is, the crew members were less likely to consult available cues, to interpret for the missing information, and to autonomously resolve the issue the more complex an activity/a task was.

Figure 4.8 shows immediate action *Contact Customer* was mentioned by owner self-performing work crews much more frequently; and Fisher's Exact Test confirmed that such a difference was of ***statistical*** significance. The odds of these crew members consulting their customers, seeking their opinions, and learning about their value were ten (10) times greater than that of specialty sub-contractor crews.

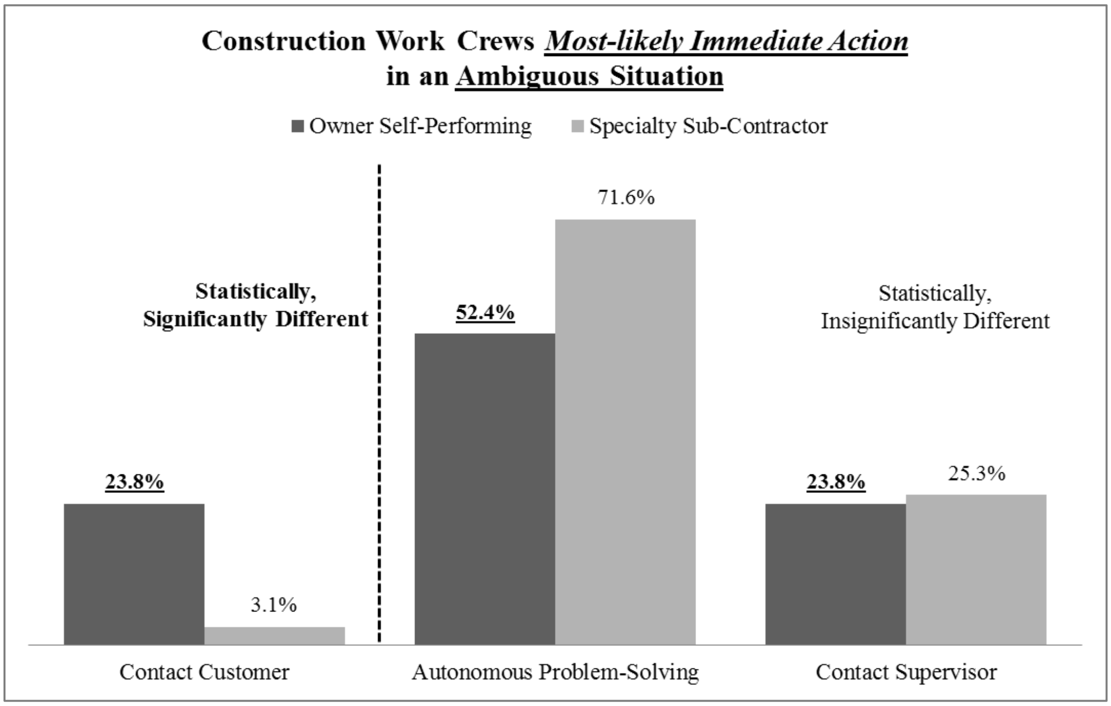


Figure 4.8 – Comparison of Immediate Actions to Ambiguous Situations with Respect to Construction Work Crews Types

In contrast, specialty sub-contractor work crews referred to immediate action *Autonomous Problem-Solving* more frequently, and with no *statistically*-significant difference. The results of Fisher's Exact statistical significance test are reported in Table 4.7.

Table 4.7 – Fisher's Exact Statistical Significance Test Result: Most-likely Immediate Actions

| **Influential Factor** | **Odds Ratio** | **p-Value** | |
|---|---|---|---|
| Contact Customer | 10 | 0.00214 | Statistically Significant |
| Autonomous Problem-Solving | 2 | 0.08214 | Not Statistically Significant |
| Contact Supervisor | 1 | 1.00000 | Not Statistically Significant |

Specialty Sub-contractor Work Crews

Presented in Figure 4.9, specialty sub-contractor work crews put their emphasis on factors *Knowledge and Skills*, *Confidence and Trust*, and *Morale and Personality*. And results of the Fisher's Exact Test revealed that specialty sub-contractor work crews had three (3) times greater odds of referring to factor *Confidence and Trust,* and *Morale and Personality*. This odds for factor *Knowledge and Skills* was two (2); and in comparison with owner self-performing crews these differences were *statistically* significant.

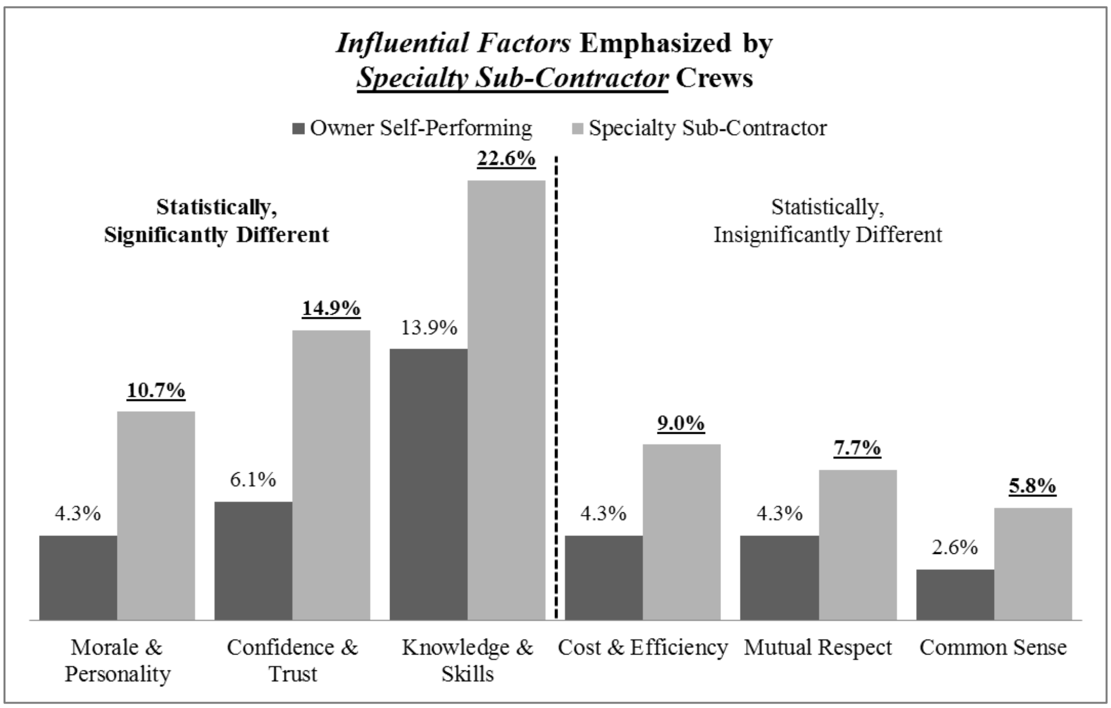


Figure 4.9 – Comparison of Influential Factors with Greater Frequencies for Specialty Sub-contractor Work Crews

Reported in Table 4.8, Fisher's Exact Test for statistical significance also presented twice-as-much odds of identifying factors *Cost and Efficiency*, *Mutual Respect*, and *Common Sense* as influential on interaction between specialty sub-contractor work crew members did not prove differences which were ***statistically*** significant.

Table 4.8 – Fisher's Exact Statistical Significance Test Result: Influential Factors of Greater Frequencies for Specialty Sub-Contractor Work Crews

| **Influential Factor** | **Odds Ratio** | **p-Value** | |
|---|---|---|---|
| Morale & Personality | 3 | 0.02676 | Statistically Significant |
| Confidence & Trust | 3 | 0.00610 | Statistically Significant |
| Knowledge & Skills | 2 | 0.02810 | Statistically Significant |
| Cost & Efficiency | 2 | 0.09029 | Not Statistically Significant |
| Mutual Respect | 2 | 0.27190 | Not Statistically Significant |
| Common Sense | 2 | 0.20760 | Not Statistically Significant |

*Take-away*: Responses provided by interviewees to an identical, general scenario and independent of trade discipline and/or crew type may be statistically different when considered from alternative points of views. Such differences are negligible because the interviews focused on an event (i.e., an ambiguous situation) and how construction skilled trades would act as a work crew in that situation. These differences however would have been significant if the concentration of problem statement was on activities/tasks a specific type of crew or a skilled trade of particular discipline (e.g., a carpenter; an electrician) would complete.

## (4.5) Summary

In this chapter findings of investigation were presented in response to research questions: first, a construction work crew was examined from the view-point of a group; and then group's conceptual Input-Process-Output (I-P-O) framework was adapted to the construction work crew. Second, data gathered from qualitative interviews with construction work crews were analyzed revealing their most-likely, and immediate action when faced with an ambiguous situation as *autonomous problem-solving*. The analyses also identified three factors of *knowledge and skills*, *confidence and trust*, and *open-mindedness* as the most influential on interactions between the members of work crews while interpreting an incomplete instruction. These findings were utilized in modeling a work crew, and in simulating interactions between its members.

## (5) Agent-Based Modeling Simulation (ABMS)

As was expressed in Section (1.3), this research addresses the of imperfect information and incomplete instruction forcing a construction work crew during an activity execution. With reference to such a problem, the goal of this investigation is to address an operational research question:

*Question: In a situation where a construction work crew receives an incomplete directive, how does the interaction between crew members impact deployment and interpretation of cues and physical hints, at the work face and its surroundings, in rendering a decision to act?*

Towards approaching this goal, one of the achievable objectives in Section (1.4) proposed to develop an Agent-based Modeling Simulation (ABMS) to explore such impacts.

## (5.1) Agent-based Model Information

The Agent-based Modeling Simulation (ABMS) simulation was constructed with two types of essential components as summarized in Table 5.1: (i) a dynamic agent which would represent a group of size $n$; and (ii) a static agent which would represent an environment of $l \times m$ neighbors with which dynamic agents would interact.

Table 5.1 – Essential Components of Developed ABMS

| Agent Type | Representation | Attribute |
|---|---|---|
| Dynamic | : User | - Cartesian coordinate<br>- Personal & professional characteristics |
| Static | : Environment | - Cartesian coordinate<br>- Color |

## (5.2) Agent-based Model Presentation

In this abstract model – as reported in Table 5.2 – the *blue circle* identifies agents and represent a *construction work crew* of *n* members. This work crew was expected to reach the only *red square* of agent environment to symbolize completion of a construction activity – each counted with variable *cycle*. Completing an activity required conducting a collection of *tasks* – which were simulated by relocating from one *white square* to another. White square (i.e., tasks) were replaced with *black squares* to abstractly demonstrate *imperfect* and *incomplete instructions*. Black squares as obstacles were considered to be incomplete instructions because each would only instruct agents to NOT relocate onto them with NO further information about the 'what-to' do. Combinations of black and white squares created cross-paths to symbolize presence of *cues* and *physical hints*. In other words, a cue was represented by availability of more than one white square onto which agents could relocate.

Table 5.2 – Presentation of Essential Components of Developed ABMS

| Entity | Description | Abstraction | Presentation |
|---|---|---|---|
| User | A construction crew of *n* members | Group of *n* agents | Blue circle |
| Environment | Construction activity | Von-Neumann neighbor | White square |
| | Completion of a construction task | Destination | Red square |
| | An incomplete instruction | Obstacle | Black square |

In short, the work crew in this agent-based model had to interact with cues and physical hints, interpret them, to decide which activity should be conducted. The *shortest path* between each white square (or rather a neighbor) and the only red square (i.e., destination) were introduced to symbolize the most efficient set of tasks to complete a construction activity.

Members of this work crew, in the meantime, were in possession of three (3) ***behavioral factors*** which were identified ***most influential*** in analyses of interview contents reported in Chapter Four. Figure 4.6 presented these factors, in order of magnitude, to be: (i) Knowledge and Skills; (ii) Confidence and Trust; and (iii) Open-mindedness. Aggregating these influential factors in the ABMS framework was a challenging task.

Skillfulness

Factor Knowledge and Skills was defined as *skillfulness* of each crew member. Skillfulness refers to skills that are obtained by a work crew member through education and/or experience which enables her/him to do the right activity, right the first time. It, thus, seemed rational to present this factor in terms of probability of correctly identifying a Von-Neumann neighbor (i.e., north; east; south; and west) which would lead the shortest path to the destination neighbor.

Confidence and Open-mindedness

With reference to Table 4.3, factor 'Confidence and Trust' was presented as *confidence* of a work crew member in ability, capability, and reliability of her/his crew-mate in doing right activity (the first time). Factor *open-mindedness* was presented as willingness of a crew member to accept choices of her/his crew-mate for (doing) right activity/task.

Probability of occurrence for these two factors were defined as *weights* to the rendered decision based on *skillfulness* of a crew member. Section (5.3) further discusses definition of such *weights*.

Crew

Given that members of a work crew are usually the same while completing an activity, another factor was introduced in addition to the three aforementioned behavioral factors in order to represent the uniqueness of *n* agents in a group. In other words, factor *Crew* was to control randomness in the experiments, and to ensure that operational values in each simulation cycle were drawn from an identical population. As Table 5.3 reports, influential factors skillfulness, confidence, and open-mindedness as well as *Crew* were assumed to follow *uniform distributions* of probabilities.

Table 5.3 – Probability Distribution Function Introduced for Influential Factors

| **Influential Factor** | **Distribution Function** | | |
|---:|---|---|---|
| Skillfulness | Uniform | $\rightarrow$ | U (0,1) |
| Confidence | Uniform | $\rightarrow$ | U (0,1) |
| Open-mindedness | Uniform | $\rightarrow$ | U (0,1) |
| Crew | Uniform | $\rightarrow$ | U (0,1) |

It should be noted that qualities of these input factors were not the scope of this investigation; and neither data was collected on skillful of work crew members, their confidence/skepticism in other's capabilities, or how open-minded/stubborn they were; nor was such information available. For the purpose of simplicity, then, uniform distributions were introduced to ensure equal likelihood of occurrence for each value.

These uniformly distributed values were considered between zero and one to represent close-to-reality scenarios; that is, neither of these factors was absolutely absent nor present – i.e., 0 or 1, respectively. Instead, each value represented a partially-absent/present input factor. These partialities assumed to be interactions enablers.

### *(5.2.1) Agent-based Modeling Environment*

As stated in Section (3.3.1), Netlogo is capable of exploring correlations between behaviors of individual entities and patterns that emerges from interactions between those entities (Wilensky, 1999). Figure 5.1 graphically presents the aforementioned essential components of the ABMS in *NetLogo* environment. Although addressed in Section (3.3.1), the use and relevance of this depiction to the problem at hand will be explained with greater details in following sections.

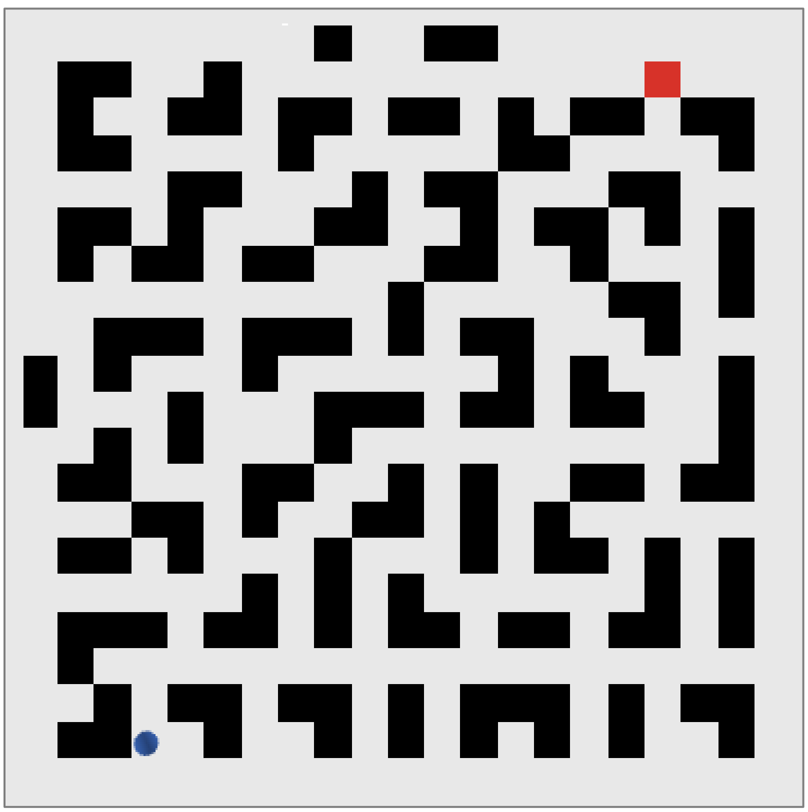

Figure 5.1 – Graphical Presentation of Developed ABMS

(5.3) Agent-based Model Simulation

As demonstrated by flowchart of Figure 5.2, in this simulation each of *n* (greater than zero) agents would relocate from one neighbor to another in a maze in order to reach a pre-determined neighbor destination through the shortest path:


Figure 5.2 – Conceptual Framework for Development of an Abstract Agent-Based Model

At any given coordinate in the environment an agent would identify its available, adjacent, Von-Neumann (i.e., N; E; S; and W) neighbors. Available neighbors for an agent would be those which were neither obstacles nor previously visited by that agent. The agent would, then, move to the neighbor which would lead the shortest path to the destination. In a situation where none of the adjacent, Von-Neumann neighbors were available, the agent was expected to relocate into its last-visited neighbor. A neighbor was reported *dead-end* in a coordinate where none of the adjacent neighbors were available and the last-visited neighbor was already re-visited – i.e., a neighbor was visited twice.

As Figure 5.3 conceptually illustrates, identifying the neighbor that leads the shortest path in any coordinate would be dependent of agent's skillfulness level. This assumption was made to adopt the results of qualitative interviews – summarized in Figure 4.6 – which identified 'Knowledge and Skill' as the most frequently-mentioned, influential factor.

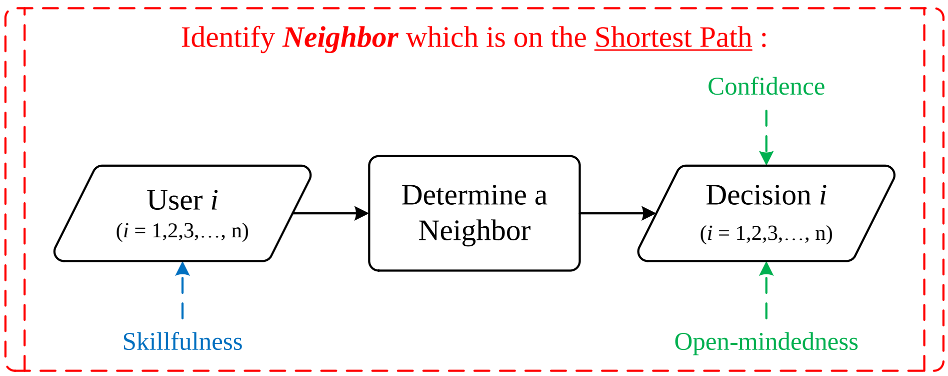


Figure 5.3 – Decision-Making Process for Agent *i* in Group of *n* Agents

The skillfulness level $p$ would be drawn from a uniform probability distribution within the range of (0 , 1) – as reported in Table 5.3. The skillfulness level $p$ meant that agent would relocate with probability of '$p$' to a neighbor on the shortest path, and would contemplate to relocate with '$1-p$' probability to a (random) Von Neumann neighbor. This binary decision was simulated by evaluating a random floating number '$r$' between zero (0) and one (1) prior to a move. An agent would relocate through the shortest path for each '$r$' smaller than '$p$' – that is, $0 < r \leq p$. The agent would consider to randomly relocate to one of its Von Neumann available neighbors for any other value of '$r$' – i.e., $p < r \leq 1$. It may be noted that one of the key role for factor Crew was, for example, to provide a *seed* value for floating number '$r$' to ensure it was drawn from the same population for each simulation cycle.

The greater this probability $p$ was the more likely an agent was to correctly orient towards the shortest path. In contrast, the lesser this probability was, the more likely the user agent was to move into a random Von Neumann available neighbor – the latter was to simulate interpretation of a cue and a physical hint which could result in inaccurate or rather unsuccessful identification of the shortest path.

This output as demonstrated in Figure 5.3 would be, then, adjusted with the ***product*** (i.e., multiplication) of the agent's confidence and open-mindedness:

$$\textbf{\textit{Decision Power}}_{\textit{user agent i}} = (\textbf{\textit{Confidence}})_{\textit{user agent i}} \times (\textbf{\textit{Open-mindedness}})_{\textit{user agent i}} \quad \ldots\ldots \quad \text{Equation 5.1}$$

Multiplication of these two factors were considered to determine the weight for each rendered decision to present a *non-compensatory* effect. $n$ weighted decisions would be rendered – i.e., one per agent $i$ – at any given coordinate, and the decision with the least magnitude of weights would be considered the one with which each agent would comply. The least weighted output was to present interactions within a group and the impact of influential factor on a group output.

The least weighted output would also represent the offset that factors confidence and open-mindedness impose; that is – for example – a relatively open-minded agent which was skeptical about another agent's decision, would have a weight that represented more of its skepticism rather than open-mindedness; or an agent which was confident in another agent yet itself was relatively stubborn, would have a weight that represented the level of its stubbornness more than confidence.

In summary, and as can be concluded from Figure 5.3, in this ABMS alternative decisions would be generated by factor *skillfulness* while power of decision-making would be controlled by factors *confidence* and *open-mindedness*.

A legitimate concern may be raised about any correlation between factor Open-minded and factor Confidence and Trust: since a strong correlation between these two factors suggests interchangeability of their values, the product (i.e., multiplication) of these values would do no justice in representation of their interactions.

As summarized in Table 5.4, two hundred and ninety eight (298) catch-phrases were clustered to describe factor Confidence and Trust – seven (7) of which were extracted from owner self-performing crew interview contents, and two hundred and ninety one (291) from specialty sub-contractor crew. Similarly, from two hundred and sixty six (266) catch-phrases describing factor Open-mindedness, twenty one (21) were from owner self-performing crew and two hundred and forty five (245) were from specialty sub-contractor crew.

Table 5.4 – Frequencies of Influential Factors with Respect to Crew Type

| | Confidence and Trust | Open-mindedness |
|---|---|---|
| **Owner Self-Performing** | 7 | 21 |
| **Specialty Sub-Contractor** | 291 | 245 |
| **Total** (Table 4.3) | 298 | 266 |

Frequencies of these catch-phrases were apportioned with respect to trades within each crew type and are reported in Table 5.5. For example, 29.21% (i.e., 85) of clustered catch-phrases for factor Confidence and Trust were mentioned by electricians, 20.27% (i.e., 59) and 26.80% (i.e., 78) by rough and trim carpenters, respectively, and 23.71% (i.e., 69) by tin-knockers in specialty sub-contractor crew.

Table 5.5 – Apportioned Frequencies of Influential Factors with Respect to Trade and Crew Type

| | | Confidence and Trust | Open-mindedness |
|---|---|---|---|
| **Owner Self-Performing** | Electrician | 28.57% | 4.76% |
| | Rough Carpenter | 28.57% | 38.10% |
| | Trim Carpenter | 42.86% | 57.14% |
| **Specialty Sub-Contractor** | Electrician | 29.21% | 28.98% |
| | Rough Carpenter | 20.27% | 22.86% |
| | Trim Carpenter | 26.80% | 24.49% |
| | Tin Knocker | 23.71% | 23.67% |

To examine whether any correlation exists between factor Confidence and Trust and factor Open-mindedness, the scatter plot of Figure 5.4 was constructed based on Table 5.5. The fitted linear-regression line resulted in a *coefficient of determination* ($R^2$) of slightly greater than 50% – which conveniently suggests a neutral correlation between these two factors. Considering an $R^2$ value of greater 0.60 to be worthwhile as rule-of-thumb, $R^2 = 0.5105$ does suggest no troublesome correlation between these two observed, influential factors.

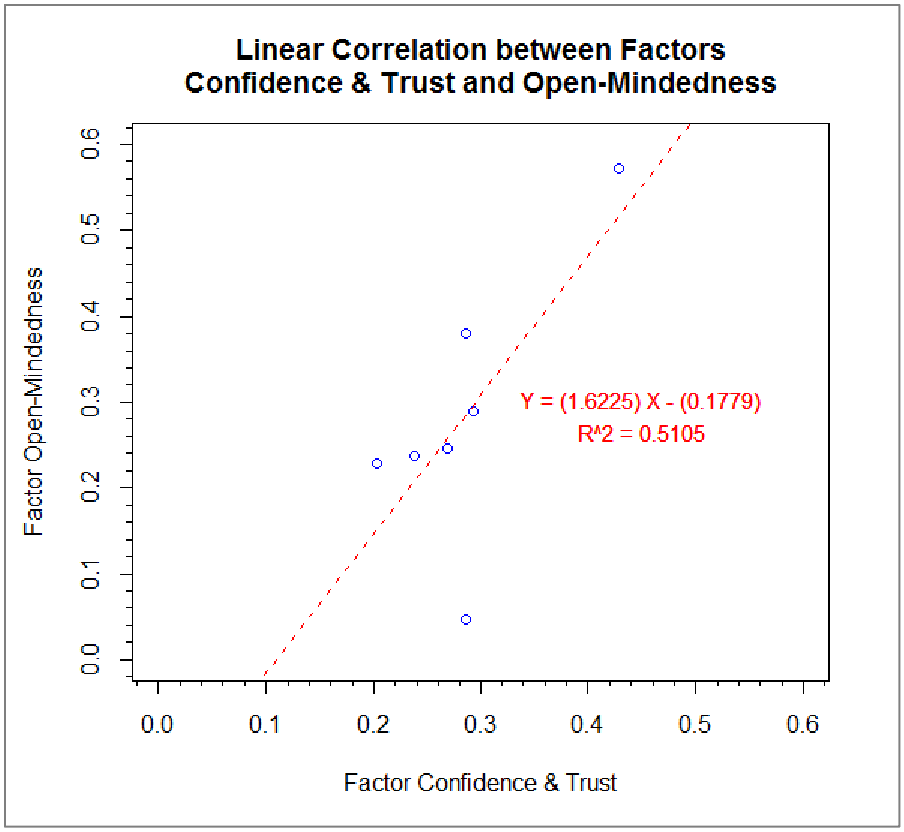


Figure 5.4 – Linear Correlation between Influential Factors Confidence & Trust and Open-mindedness

(5.4) Agent-based Model Result

This agent-based model was simulated for a total of 199,948 cycles. Section (5.5.2) will explain the logic for conducting this number of repetitions. One (1) cycle of simulation was completed when the agents reached the destination. Simulation cycles were independent from one another – i.e., each was an attempt by agents to reach the destination passing through thirty two (32) non-diagonal neighbors with NO learning from the previous experiment(s). Considering the placement of black and white squares (i.e., layout of the maze in Figure 5.1), thirty-two represented the most efficient (i.e., shortest) performance.

Each cycle was to symbolically represent that activity duration would change when construction work crew was forced to take cues and physical hints and interpret them in order to determine 'what-to' do. Under the assumption of integrity, in this ABMS agents followed their moral principles and did NOT intentionally take wrong cues nor interpret them inaccurately to benefit from a lengthy activity.

In each simulation cycle, three (3) dependent output variables were measured:

(i) Number of neighbors visited: number of neighbors *n* agents group visited to relocate between two specific neighbors was counted to represent the operation time. With the perspective of construction project management, this symbolizes *effectiveness* (i.e., doing right things) of resources utilization in completing an activity/a task.

(ii) Number of neighbors re-visited: number of neighbors *n* agents group re-visited once – i.e., visited twice – was collected to represent the concept of *rework* in construction operations. In terms of *efficiency* (i.e., doing things right), it was to represent the amount of resources utilized to undo a completed wrong activity, and to do the correct activity.

(iii) Number of neighbors dead-end: number of neighbors dead-end that the *n* agents group visited was tallied. Relocating into a dead-ended neighbor was to simulate that every feasible option was exhausted. With respect to construction project management/ operation, this output variable would represent demands for more instruction/ information – which would often dictate inputs from superintendent, project engineer, etc.

The descriptive measures of these outputs summarized in Table 5.6 reveal two (2) major points: first – population size of agents contributed in variations of each outputs category. The maximum number of neighbors visited and dead-end were the least (i.e., 2,123 and 69, respectively) for the group of 5 agents, while those for a group of two agents were the most (i.e., 3,886 and 195, respectively). In a different fashion, groups of two and three agents re-visited respectively the least (i.e., 159) and the most (i.e., 176) number of neighbors. These measures may imply that a group of agents – in comparison to one – influence the outputs of this model.

Table 5.6 – Statistical Descriptive Measures for ABMS Outputs Variables

| **Neighbors** | **Population** | **Minimum** | **Maximum** | **Mean** | **Standard Deviation** |
|---|---|---|---|---|---|
| Visited | 1 agent | 32 | 2,711 | 71.74 | 111.05 |
| | 2 agents | 32 | 3,886 | 64.93 | 82.47 |
| | 3 agents | 32 | 2,353 | 60.74 | 63.85 |
| | 5 agents | 32 | 2,123 | 56.82 | 48.20 |
| Re-visited | 1 agent | 0 | 167 | 6.61 | 11.97 |
| | 2 agents | 0 | 159 | 6.62 | 11.83 |
| | 3 agents | 0 | 176 | 6.56 | 11.65 |
| | 5 agents | 0 | 168 | 6.40 | 11.35 |
| Dead-end | 1 agent | 0 | 116 | 0.70 | 3.71 |
| | 2 agents | 0 | 195 | 0.32 | 1.96 |
| | 3 agents | 0 | 91 | 0.15 | 0.98 |
| | 5 agents | 0 | 69 | 0.04 | 0.46 |

Second – values in each outputs category were more clustered around smaller values as population of agents grew larger. For instance, mean number of neighbors visited decreased by (roughly) 20 percent from ≈ 72 to ≈ 57 for one and five agents respectively and the numbers of neighbors 5 agents visited were 57 percent more clustered around mean than those of 1 agent (i.e., standard deviations of ≈ 111 and ≈ 49 for one and 5 agents, respectively).

## (5.5) Agent-based Model Analysis

In context of this research dissertation topic, the aforementioned dependent output variables were analyzed to determine: (a) whether influential factors on interaction among work crew members would cause variation in operation time and efficiency of resources utilization; would result in rework and generate waste; and (b) whether they would increase the likelihood of demand for assistance – e.g., supervisor instruction/involvement.

### *(5.5.1) Exploratory Analysis*

In order to learn about distributions of outputs, and to evaluate changes of outputs with respect to input factors a series of *exploratory statistical analyses* were conducted.

#### Construction Work Crew Size

The first step in process of analyses was set to understand whether changes in outputs would be observed at large with respect to a group size greater that one agent. Therefore, the ABM was simulated with population of one, two, three, and five agents, for 199,948 cycles each. Then, to make interpretation straightforward, probability density functions were constructed for outputs of each population size. The PDF plot enables an observer to compare magnitudes of probability — i.e., the area under each distribution curve corresponding to a range of data.

In Statistics terms, a *Probability Density Function* (PDF) estimates the probability that a random variable belongs within a defined range of values. In other words, it defines the likelihood of occurrence for a specific event. Figure 5.5, the probability density of number of neighbors visited for different group sizes, demonstrates a pattern in which the likelihood that an operation time would fall within a particular range varies as group sizes change. This change may be interpreted in favor of the optimal number of neighbors visited that there is a greater likelihood that this number is optimal in a group of fewer agents. It can also be interpreted in favor of group size – that non-optimal number of neighbors visited would be less likely to occur in groups of more agents in comparison with those of fewer – in case of this investigation from five to one; although the variations of outputs were not as significant in magnitudes between groups of two and five agents as was between those of one and five (or even one and two).

The vertical dotted line in Figure 5.5 shows the value of optimum number of neighbors visited established at the thirty two (32) steps in the maze (i.e., Figure 5.1).

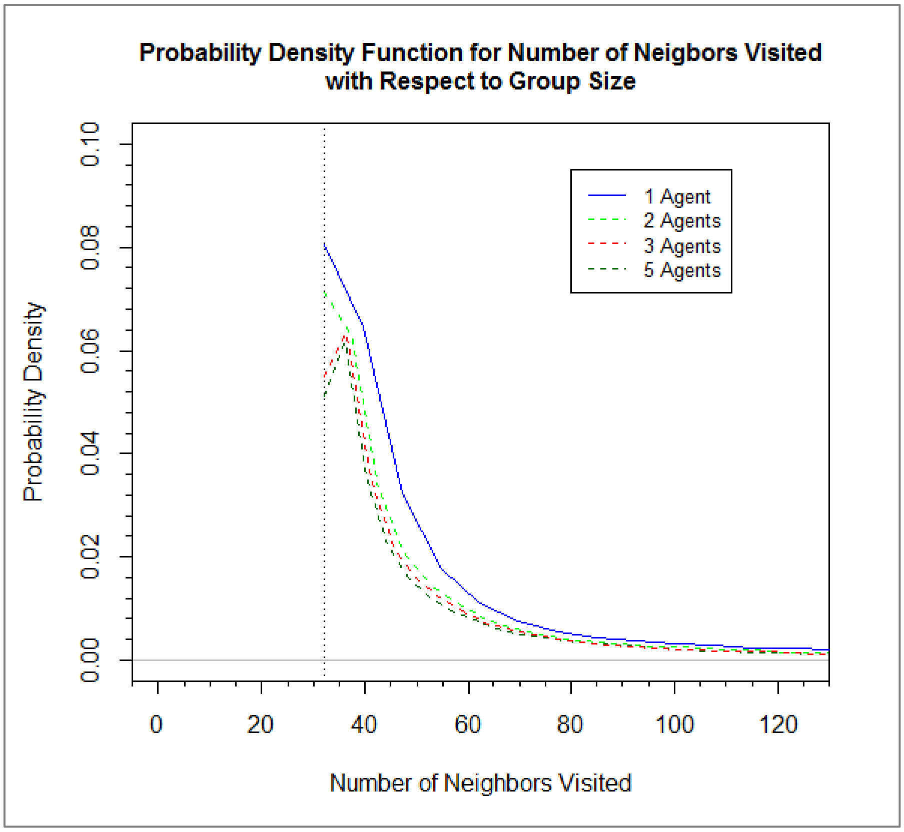


Figure 5.5 – Variation in Number of Neighbors Visited with Respect to Group Size

Although work crew size by itself was not the focal point in this research dissertation as one of the sources for variation of outputs, it was discussed as the facilitator of interaction between members of a crew (James, 1951; O'Dell, 1968). With reference to Figure 5.3 it could be claimed that in a case of only one agent, neither factor confidence nor open-mindedness affected outputs as there existed no interactions; and that skillfulness was the solely influential one. In contrast, all three factors influenced outputs in a case of two or more agents. The next step was set to evaluate the impact(s) of these three factors on ABMS outputs.

A population of size two was assumed to represent the concept of ‘fair share’ in participations; and to reasonably eliminate the ‘majority-rule’ effect.

*Take-away*: A group contributes to change of ABMS outputs.

Throughout analyses, as Section (3.3.2) discussed in details, a set of reference values were introduced not only to make the process simple and straightforward, but also more meaningful and realistic.

Analysis Reference Value

Table 5.3 reported that influential factors were assumed to carry probability distributions between zero and one – i.e., U (0,1). Arithmetic mean value (i.e., 0.50) of these independent input factors was chosen as the dividing point in evaluating their influence on dependent output variables. As demonstrated in Figure 5.6, four regions/quadrants were constructed each of which assign an agent with a value of greater or lesser than 0.50.

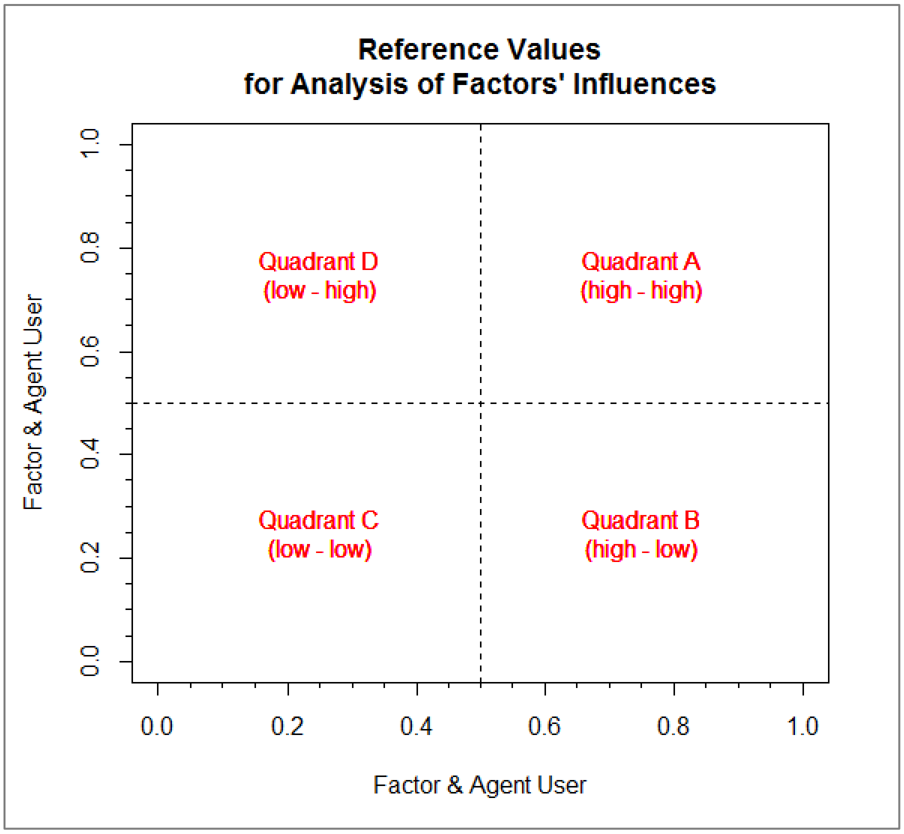


Figure 5.6 – Graphical Presentation for Analysis Reference Value

<u>Construction Work Crew Skillfulness</u>

In order to explore whether a correlation existed between variation in outputs and skillfulness level of each agent, frequency analysis for number of neighbors visited was conducted. Reported in Table 5.7, (roughly) similar portions of <u>199,948</u> simulation cycles resulted in <u>*optimal*</u> and <u>*least optimal*</u> number of neighbors visited – i.e., respectively, 17.52% cycles visited <u>32</u> neighbors and 18.30% visited more than <u>72</u>. Levels of skillfulness for agents were plotted in terms of its corresponding value being either ends of this range.

Table 5.7 – Frequency Analysis of ABMS Output: Number of Neighbors Visited by Two Agents

| Number of Neighbors Visited | Frequency | Percent of Total |
|---|---|---|
| ≤ 32 | 35,022 | 17.52% |
| > 32 and ≤ 40 | 70,062 | 35.04% |
| > 40 and ≤ 48 | 27,229 | 13.62% |
| > 48 and ≤ 56 | 15,052 | 7.53% |
| > 56 and ≤ 64 | 9,599 | 4.80% |
| > 64 and ≤ 72 | 6,390 | 3.20% |
| > 72 | 36,594 | 18.30% |

29.15%

81.70%

In Figure 5.7, population in color 'blue' represents simulation cycles in which 32 neighbors were visited; and population of those in which more-than 72 neighbors were visited is in color 'red'. The scattered population was then divided into four quadrants to match the 'analysis reference value'. It can be observed that:

(v) *Quadrant A* accommodated majority of simulation cycles in which 32 neighbors were visited;

(vi) *Quadrant C* clustered with a great portion simulation cycles in which more-72 neighbors were visited; and

(vii) *Quadrants B & D* were populated by a combinations of simulation cycles – those with optimal number of neighbors visited, and those with non-optimal.

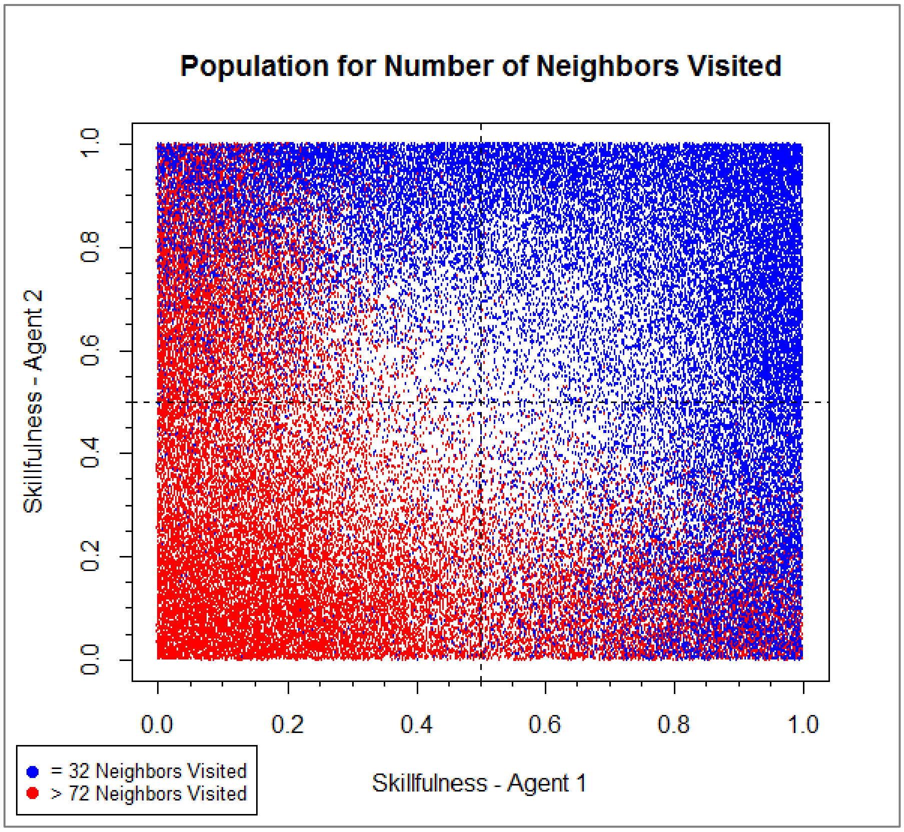


Figure 5.7 – Skillfulness Level for Two Agents with Respect to Simulation Cycles Outputs

In order to better understand the influence of different levels of skillfulness on likelihood that number of neighbors visited would deviate from its optimum, PDF curves were constructed. Illustrated in Figure 5.8, numbers of neighbors visited were presented in terms of independent input factor skillfulness. In compliance with analysis reference value, factor skillfulness was divided into four levels – quadrants A, B, C, and D. Each curve represents a quadrant; and the area under each curve defines the likelihood that a range of particular values would populate that quadrant.

The range [32 , 40] was the case in more than fifty-two percent of simulation cycles. According to Table 5.7, the likelihood that number of neighbors visited would fall within limits of this range was the greatest for skillfulness values of quadrant A, the quadrants B and D. This likelihood was the least for skillfulness values of quadrant C. In contrast, for the range (40 , 72] which according to Table 5.7 was the number of neighbors visited also in (roughly) one-third of simulation cycles, skillfulness values of quadrant C provided the greatest likelihood in comparison with those of quadrants A (i.e., the least), B, and D.

Dotted vertical lines in color ‘black’ define the boundaries of these ranges. It should be noted since density distributions for dependent outputs of quadrants B, and D are similar, only population of outputs correspond with quadrants B was considered for further analyses.

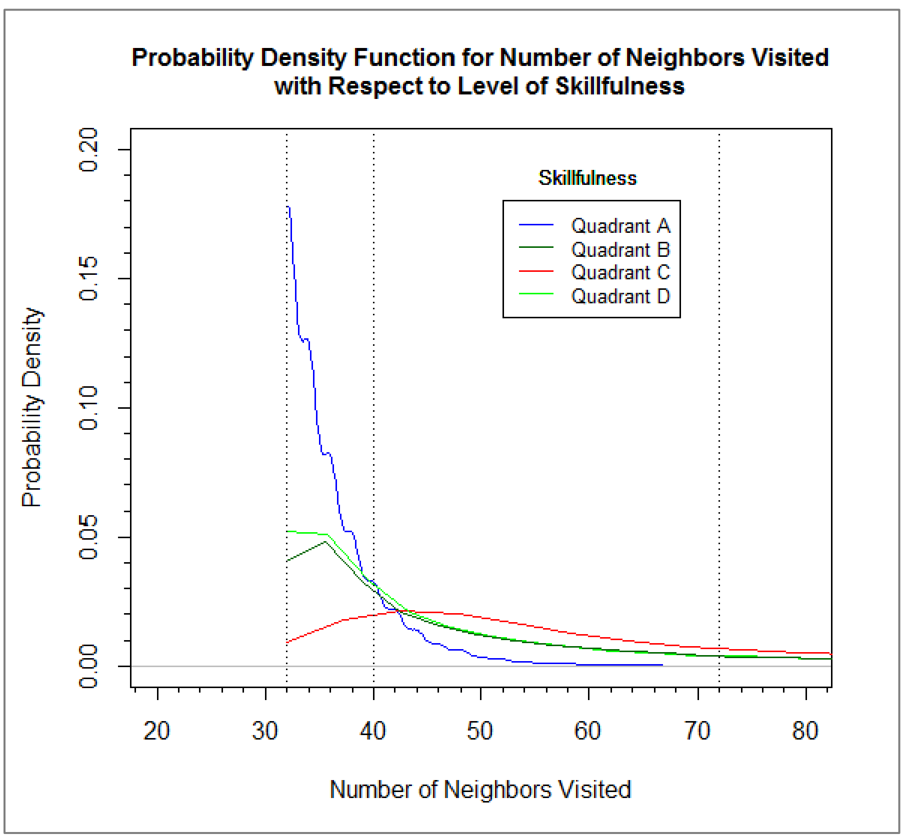


Figure 5.8 – Number of Neighbors Visited with Respect to Skillfulness Level for Two Agents

With reference to Section (5.3), a rational explanation for clusters of values in quadrants A and C of Figure 5.7 and also their greater likelihoods in Figure 5.8 would be the likelihood that *n* decisions – two, in this case – at a given location were similar. Moreover, at any location the likelihood of dissimilar decisions was greater for skillfulness values in quadrants B and D. The latter explanation is based on the fact that those values were drawn from different sections of skillfulness spectrum – value of skillfulness for one agent was greater than 0.50 while that of the other agent was lesser than 0.50. This unlikelihood for similarity of decisions, unarguably translates to greater likelihood of interaction between agents in process of determining the interim destination.

It can be argued, in other words, that greater volumes of interactions between agents took place in simulation cycles populated the quadrants B and D; and consequently a trigger for greater involvement of factors confidence, and open-mindedness. Thus, further analyses focused on those populations (i.e., curves in color 'light green' and 'dark green').

*Take-away*: Although layout of agent environment could play roles in similarity and dissimilarity of decisions since neighbors' availability was a requisite, nevertheless the more similar were levels of skillfulness for each agent, the greater was likelihood that both agents would choose the same neighbor.

<u>Construction Work Crew Confidence and Open-mindedness</u>

In Figure 5.9 probability density functions are presented with respect to different levels of confidence and open-mindedness – given a particular range of skillfulness: the continuous curve in color 'black' represents probability density for number of neighbors visited in simulation cycles that skillfulness values were drawn from quadrant D. This PDF curve was then adjusted for confidence and open-mindedness values of quadrants A, B, and C. It can be observed that likelihood for number of neighbors visited to fall in range [32 , 40] was the least in magnitude when confidence and open-minded values were withdrawn from quadrant C. This likelihood rose for those values of confidence and open-mindedness withdrawn from quadrant B.

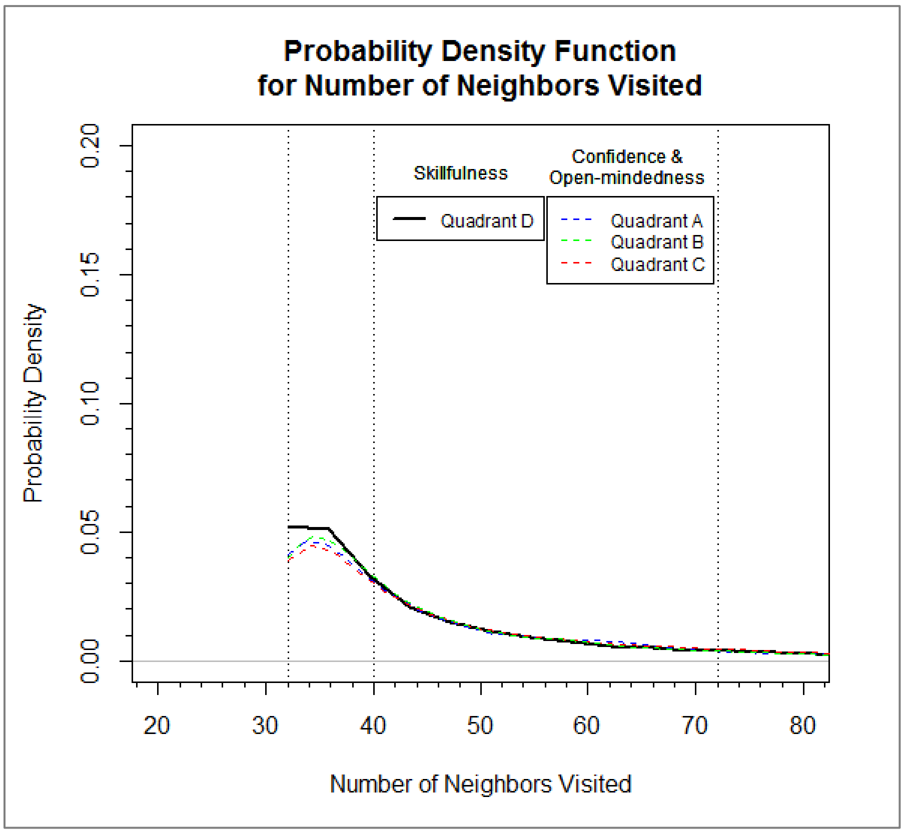


Figure 5.9 – Number of Neighbors Visited for Skillfulness Level 'D' with Respect to Confidence, & Open-mindedness

One explanation for such behavior would be the intensity of interaction between agents. With reference to Figure 5.3, different quadrants of values for skillfulness level were likely to result in dissimilar decisions; and that in turn prompted interactions. Confidence and open-mindedness levels from different quadrants intensified such interactions to a greater degree, which consequently influenced outputs of the process. In contrast, the behavior of PDFs in

Figure 5.10 can be explained by lesser likelihood of rendering dissimilar decisions with skillfulness values of quadrant C – which lessened the intensity of interactions between agents; hence the smaller area under adjusted PDF curve for quadrant B values of confidence and open-mindedness.

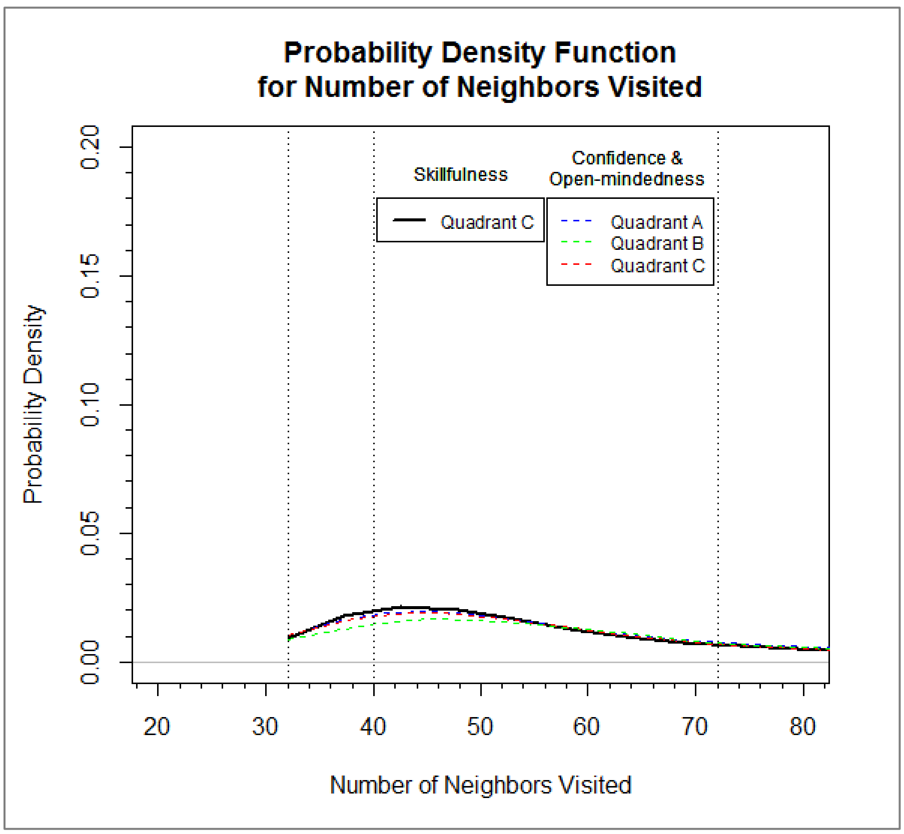


Figure 5.10 – Number of Neighbors Visited for Skillfulness Level 'C' with Respect to Confidence, & Open-mindedness

*Take-away*: Dissimilarities of decisions agents rendered triggered interactions between input factors; and these interactions in turn contributed to variations of outputs.

This section, so far, demonstrated that interactions between *n* agents – two in this case – would be enabled by different levels of their skillfulness; that such interactions would be intensified based on agents' levels of confidence and open-mindedness; and that intensity of these interactions in turn would influence output variables of this ABMS. In order to explore how influential each of these three factors were – or rather to investigate how sensitive the outputs of ABMS were to these three factor – or even how much each of these three factors contributed in variation of ABMS outputs, *Sensitivity Analysis* was conducted.

*(5.5.2) Sensitivity Analysis (SA)*

The main objective of analyses presented in this section was to explore sensitivity patterns induced by input factors in ABMS outputs. SimLab software, as mentioned in Section (3.3.2), was employed, and variations in outputs of 199,948 ABMS cycles were decomposed with association to their corresponding input factors. Table 5.8 summarizes results of analyses in which values of columns '*First-Order Index*' and '*Total-Order Index*' respectively represent the first and last segments of the *variance-based sensitivity analysis* equation:

$$V = \left(\sum_{i}^{k} V_i\right) + \left(\sum_{i<j}^{k} V_{ij}\right) + \left(\sum_{i<j<m}^{k} V_{ijm}\right) \text{ ............................................... Equation 5.2}$$

Table 5.8 – Sensitivity Indexes for Variation of Output: Number of Neighbors Visited

| **Influential Factor** | **First-Order Index** | **Total-Order Index** | **Difference of Indexes** |
|---:|:---:|:---:|:---:|
| Skillfulness | 28.68% | 91.76% | 63.08% |
| Confidence | 8.50% | 66.32% | 57.82% |
| Open-Mindedness | 8.77% | 67.82% | 59.05% |
| Crew | 0.0035% | 55.90% | 55.89% |

| | Independent | Interaction |
|---:|:---:|:---:|
| Apportioned Contributions | 45.95% | 54.05% |

The first-order indexes values define the contributions of each input factors, when independently fixed, in variation of outputs. The summation of these values explain how much of outputs variations was caused by input factors, independently. The values of total-order indexes determine overall contributions of each input factors in variations of outputs – that is, the contribution of each input factors when independently fixed plus interactions of such factor with other ones. Table 5.9 discusses the importance of these values in terms of orders of their magnitudes.

Table 5.9 – Guideline for Interpretation of SimLab Sensitivity Analysis Output
Adopted from Source: (Ligmann-Zielinska & Sun, 2010)

| **SimLab Analysis Result** | | **Interpretation** |
|---|---|---|
| First-Order Index | → | A relatively great value for this measure represents a corresponding significantly-influential input factor. Sum of these indexes determines the portion of outputs variations caused by input factors independently (i.e., no interaction with other input factors) |
| Total-Order Index | → | A relatively small value for this measure represents a corresponding non-influential/insignificantly influential input factor. |
| Difference of a First- and a Total-Order Index | → | A relatively great value of difference represents a corresponding input factor with a significant intensity of interaction with other input factors. Such input factor influences variation of outputs through interactions with other input factors, regardless of its significant/ insignificant independent influence. |

Based on sensitivity indexes summarized in Table 5.8, it can be concluded that input factors skillfulness, confidence, open-mindedness, and crew independently caused 45.95 percent of outputs variations in this AMBS – with the most significant influence of 28.68 percent by factor skillfulness; and that interactions between all four input factors, as presented in Figure 5.11, contributed to more than a half of variations in the outputs – i.e., 54.05%. The fact that values for first-order indexes summed less than 100 percent demonstrate the complexity of this model and an additive correlation between impacts of these input factors on variations of model outputs.

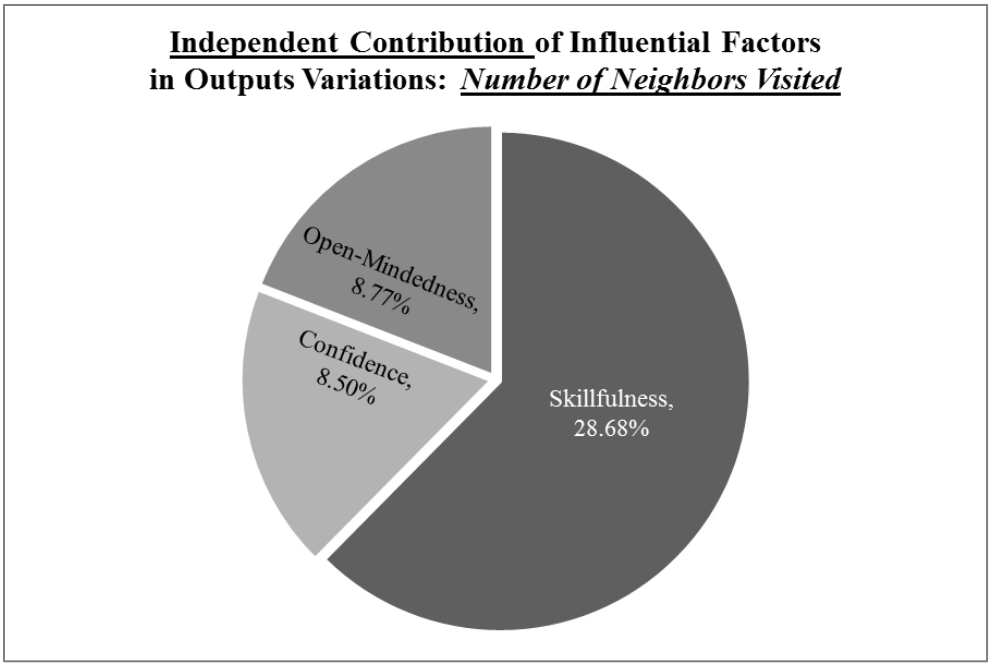


Figure 5.11 – Independent Contribution of Input Factors to Outputs Variations: Number of Neighbors Visited

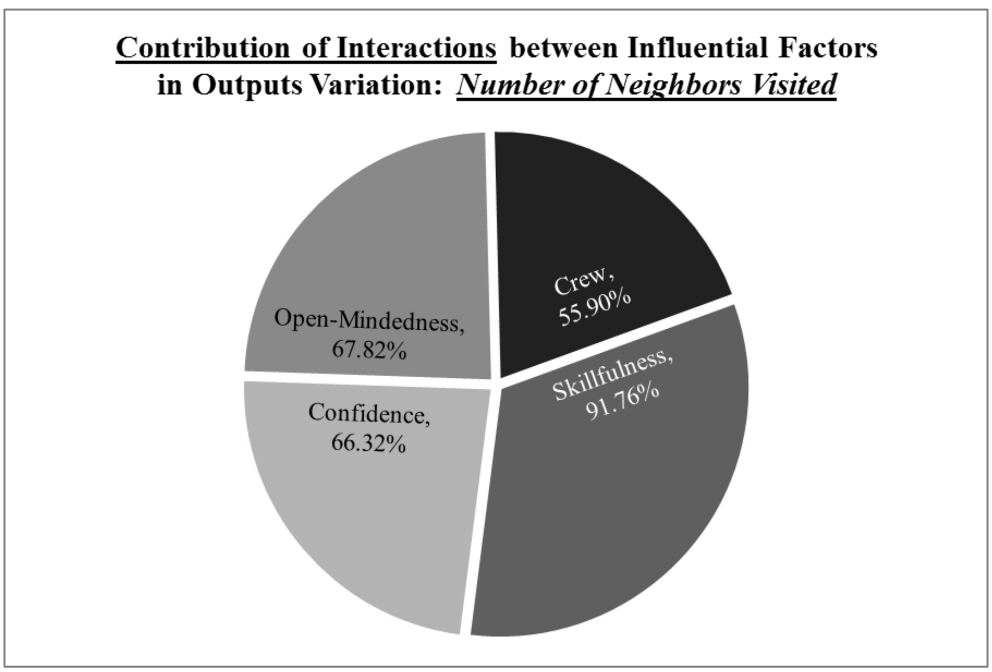


Figure 5.12 – Contribution of Input Factors Interactions to Outputs Variations: Number of Neighbors Visited

Moreover, considering the total-order index values it can be understood that although factors confidence and open-mindedness did not independently influence model outputs by much, both interacted with other factors and contributed to outputs variations. Similarly, factor crew-type which represented 'randomness' in ABMS independently impacted outputs by close to zero percent, and yet interacted with other factors to contribute in outputs variations. Intensities of such interactions were revealed by the differences of sensitivity-index values: factor skillfulness brought about the largest portion of interactions; then factors open-mindedness and confidence; and factor crew-type interacted with other factors the least.

Comparable to those for output Number of Neighbors Visited, Table 5.10 summarizes sensitivity indexes for output Rework. Based on values of first-order and total-order indexes it can be concluded that the majority of variations in output – i.e., 54.63 percent – was caused by interactions between input factors in which factor skillfulness led the intensity followed by factors open-mindedness, confidence, and crew-type.

Furthermore, it can be understood that only 45.37 percent of variations in outputs might be explained by independent contributions of each input factor – with the greatest contribution of 28.64 percent by factor skillfulness. The only notable difference between sensitivity indexes of these two output variables was for input factor crew-type: although negligible in comparison to others, its independent contributions to variations of outputs was increased by 60 percent from 0.0035 to 0.0056.

Table 5.10 – Sensitivity Indexes for Variation of Output: Rework

| Influential Factor | First-Order Index | Total-Order Index | Difference of Indexes |
|---|---|---|---|
| Skillfulness | 28.64% | 92.09% | 63.45% |
| Confidence | 8.34% | 65.90% | 57.56% |
| Open-Mindedness | 8.38% | 66.20% | 57.82% |
| Crew | 0.0056% | 52.05% | 52.04% |

| | Independent | Interaction |
|---|---|---|
| Apportioned Contributions | 45.37% | 54.63% |

As a pattern in this ABMS, interactions between input factors apportioned for greater contributions than their independent influences in outputs variations. As Table 5.11 reports, this contribution of 57.65 percent was an increase of (about) 7 percent from those of outputs Number of Neighbors Visited, and Rework. Intensity of interactions between input factors increased in case of this output with a notable spike for crew-type – i.e., from 55.89 (for output number of neighbors visited) and 52.05 (for output rework) to 71.92 percent.

Independent influences of input factors confidence, and open-mindedness in variations of outputs also experienced an increase of (roughly) 25 percent in comparison with those of other outputs.

Table 5.11 – Sensitivity Indexes for Variation of Output: Call for Assistance

| Influential Factor | First-Order Index | Total-Order Index | Difference of Indexes |
|---|---|---|---|
| Skillfulness | 21.18% | 89.58% | 68.40% |
| Confidence | 10.53% | 76.60% | 66.07% |
| Open-Mindedness | 10.34% | 77.04% | 66.70% |
| Crew | 0.0042% | 71.92% | 71.92% |

| | Independent | Interaction |
|---|---|---|
| Apportioned Contributions | 42.05% | 57.95% |

Figure 5.13 graphically compares the intensities of interactions between input factors for each output variable.

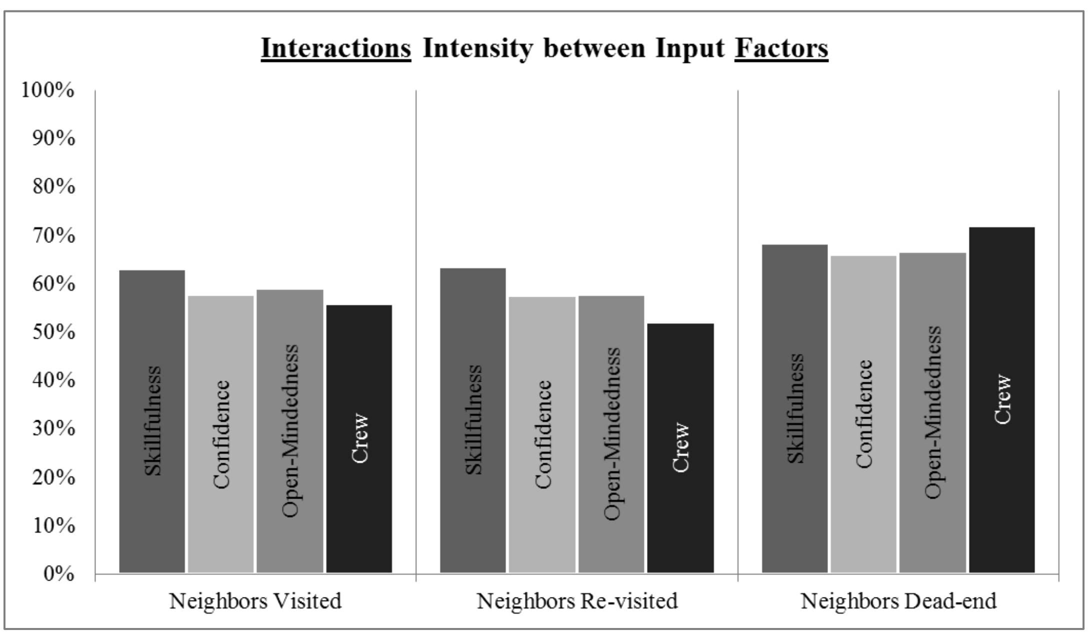


Figure 5.13 – Comparison of Interactions Intensity of Input Factors with Respect to Outputs Variables

Number of Simulation Cycles

Figure 5.14 demonstrates the altering behaviors of first-order sensitivity indexes values for numbers of simulation cycles between 500 and 300,000. The dotted, vertical line in color 'black' marks 110,000 simulation cycles; and those horizontal represent the range of 3.50 percent difference in sensitivity indexes. As can be observed, values of each index relatively stabilized for a number of 110,000 and greater simulation cycles.

The number of 199,948 repetitions – displayed by a solid, vertical line in color 'dark green' – was selected since it roughly averaged the range of stabilized simulation cycles. Note that the number of 199,948 receptions was in accord with the sample of values for input factors generated in SimLab. As introduced in Section (3.3.1), software SimLab uses Monte Carlo random sampling technique to generate pseudorandom numbers in some (user defined) iterative fashion. This sample is then supplied as input factors for *Uncertainty Analysis* (UA) and *Sensitivity Analysis* (SA) of models.

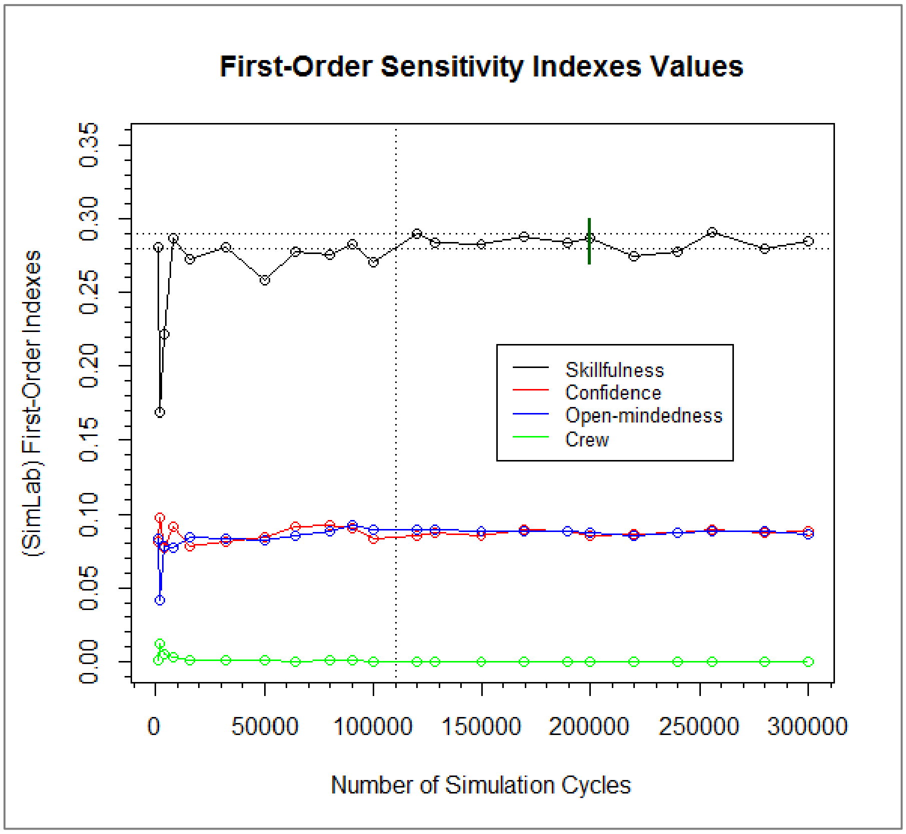


Figure 5.14 – Variations in Sensitivity Indexes with Respect to Number of Simulation Cycles

*Take-away*: Input factors contributed to variations in outputs not only independently, but also through interactions with one another; and in case of this ABMS, the latter apportioned greater contributions than former. Therefore, even though an input factor insignificantly influenced the variations of outputs, its interactions with others were found significant and impactful in variations of outputs.

## (5.6) Summary

In Chapter Five an agent-based model was developed based on conceptual frameworks of a construction work crew's Input-Process-Output (I-P-O) and cue-interpretation introduced in Chapter Four. This ABM was translated into *NetLogo* programmable modeling environment, and then simulated for 199,948 cycles with a numerical experiment designed in software *SimLab*. Number of neighbors visited (i.e., operation time), re-visited (i.e., rework), and dead-end (i.e., call-for-assistance) were collected as outputs of simulation cycles. Exploratory statistical and sensitivity analyses were conducted revealing that population size for agents, levels of skillfulness, confidence, and open-mindedness contributed to variations of ABMS outputs; that greater skillfulness, confidence, and open-mindedness increased the likelihood of visiting lesser number of neighbors; and that this ABMS was the most sensitive to level of skillfulness, and then levels of confidence and open-mindedness.

## (6) Conclusion

The problem addressed in this research dissertation was the interpretation of cues and physical hints by a construction work crew in an ambiguous situation and where explicit directives were absent. As explained in Chapter One, this investigation further posited that interactions between members of a construction work crew would impact interpretation of cues and would thus impose influences on work crew performances. In order to explore this conjecture the following objectives were achieved:

(i) Factors which would influence interactions between members of a construction work crew were identified;

(ii) (Reference) frameworks to conceptually address construction work crew interactions, and cue-interpretation were developed; and

(iii) An abstract agent-based model based on the conceptual reference frameworks was developed and exploited for deriving insights.

To satisfy these aforementioned objectives, five (5) phases were undertaken: in *Phase One* literature relevant to Small Group research was surveyed. As reported in Chapter Two, it was understood that a group was defined to be:

(a) a collection of two or more individuals;

(b) who are functionally related;

(c) who continuously engage in a direct (e.g., face-to-face) interaction(s); and

(d) who purposively perform toward a common objective(s).

Focusing on the dynamics of a small group – and NOT its groupness – it was also learned that a reference framework Input-Process-Output (I-P-O) had been used to conceptually present group function; and that because previously-identified factors influencing a group process were almost always case-specific, it was important to identify factors relevant to construction industry and decision-making in presence of cues and physical hints.

Review of literature pertinent to construction work crew decision making identified the gap in addressing improvisation versus cue interpretation – that is, in absence of explicit directives, and when instructions were incomplete and information was imperfect, the work crews were known to improvise; and this research dissertation argued that work crews also take cues, respond to physical hints, and accordingly take actions.

In *Phase Two* qualitative interviews with a population of construction skilled trade workers revealed that majority of work crews were likely to autonomously solve a problem caused by ambiguity in workface – instead of contacting their supervisors, or consulting with their customers. Also, as Chapter Four summarized, interviewees identified fourteen factors influential to their decision-making processes in presence of surroundings cues and physical hints. The factors Knowledge and Skill, Confidence and Trust, and Open-mindedness were the most-frequently mentioned ones.

In *Phase Three*, a references frameworks were developed to conceptually present: (i) phenomenon of cue interpretation in construction workface; and (ii) a work crew operation in process of interpreting a cue and physical hint.

*Phase Four* focused on translating these frameworks into an agent-based modeling simulation – ABMS.

In *Phase Five*, ABMS experiments were conducted for a total of 199,948 cycles in which a series of three outputs were determined: (i) number of neighbors visited; (ii) number of neighbors re-visited; and number of dead-end neighbors reached. Results of exploratory statistical analyses and sensitivity analyses (SA) were reported in Chapter Five and are discussed in the next Section (6.1).

## (6.1) Discussion

The analyses presented in Chapter Five were conducted to explore interactions between work crew members and to better understand influences such interactions impose on interpretations of cues and physical hints. In order to discuss these findings with respect to this research dissertation the following research question is considered:

Question*: How can these analytical results be interpreted with respect to interpretation of cues in a construction work crew?*

It was explored whether being a group contributed to variations of ABMS outputs. Results of analyses demonstrated that levels of uncertainties in model outputs would vary for work crews of different size (i.e., number of members). This variation is an implication of some processes or rather interactions between members of a crew, and ~~it~~ does not imply that a construction work crew of one member may be extra efficient, more productive, and/or likely successful than that of two or more members in accurately interpreting the “what-to do’s” based on surroundings cues and physical hints. In other words, (activity) performance would be negatively impacted by presence interpretation of cues and physical hints, even though it appears to improve with increasing crew size.

As Figure 6.1 suggests, a crew of larger size would experience a better performance in variation of operation time due to greater volume of interactions between crew members in decision-making and cue-interpretation. However, it does not necessarily improve the performance mean.

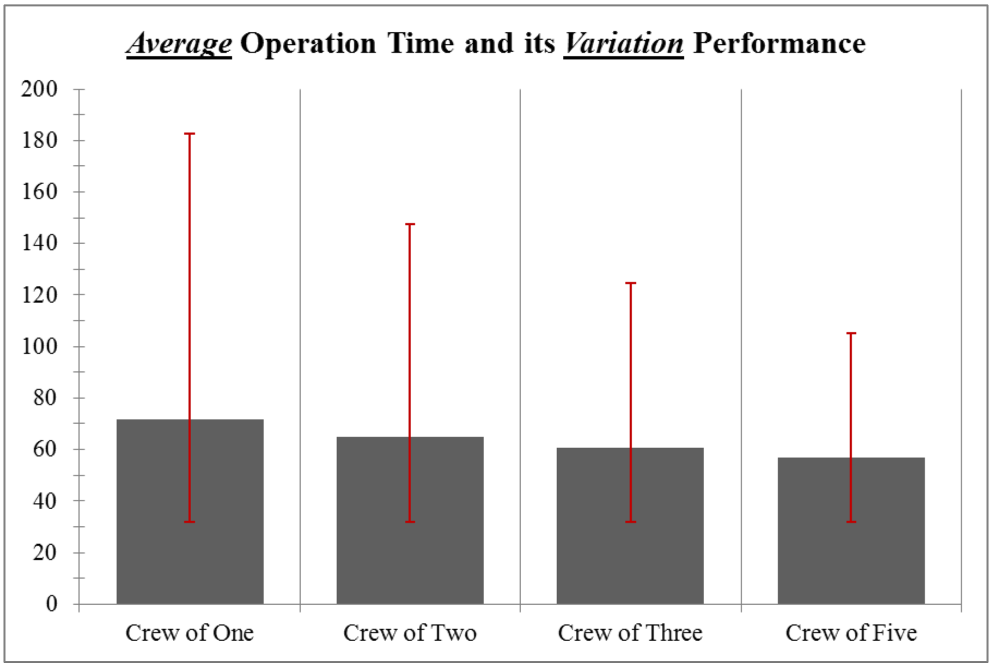


Figure 6.1 – Average Operation Time and Variation Performance with Respect to Crew Size

Crew size facilitates the intensity of interactions between crew members and, consequently, contributes to predictability and reliability of work flow. Nevertheless, interaction is not enough to eliminate variations in performance and/or work flow. In the meantime, it is important to note that increasing size of a crew may not be advised in solitary and with no considerations of technical necessities, and adverse impacts of crowding phenomenon.

The analyses also showed that, with respect to level of skillfulness, a homogeneous group rendered (more) similar decisions; and that heterogeneity of skillfulness values propagated greater uncertainties in distributions of outputs. Skillfulness in this investigation symbolized the knowledge of *how-to* technically (i.e., from a technical stand point) accomplish a task. The knowledge about *what-to* do considered in terms of directives (e.g., pieces of information and instructions) – the absence of which this research argues is the trigger for cue-interpretation. Those in considerations, the analyses can imply that a construction work crew of comparable (i.e., homogeneous) skillfulness levels may complete identical tasks more efficiently in comparison with a heterogeneously-skilled crew. Homogeneity of crew members in skillfulness is argued to result in similar decisions which in turn decreases not only the intensity of interactions but also their impacts. That is, crew members take similar cues and/or interpret them similarly in order to determine the "what-to do's"; which eliminate great intensities of interactions to introduce the final decision.

On the other hand, it may be inferred from these analytical results that heterogeneity of skillfulness enables and encourages work crew members to interact for rendering the final decision as each member takes a different cue and/or render a different interpretation of that – which in turn becomes more influential. It can be further inferred that the quality of interactions output depends on confidence and open-mindedness levels of each construction work crew member: the more the work crew members are heterogeneous in confidence and/or open-mindedness, the greater influences their interactions impose.

Sensitivity analyses of ABMS outputs, as compared in Figure 6.2, revealed that skillfulness of crew members may be introduced as a factor which will need more attention since it strongly impacts amount of rework and waste, operation time, and efficiency in resources utilization, and also frequency of call-for-assistance, respectively. As previously mentioned, one side of knowledge and skills is about directives (information and instruction), lack of which invites cues and surroundings physical hints in determination of *what-to* do. This is, thus, aligned with the problem stated in Section (1.3) since the more complete and more explicit is a directive, the more efficiently it is executed; the less amount of waste is generated; and the fewer occasions when supervisory-assistance is required. It is of value to note that *how-to* do represents the technical aspect of knowledge and skillfulness – which greatly influences amount of rework and waste, and frequency of call-for-assistance. These in turn will impact operation time due to lack of knowledge on how to complete a task.

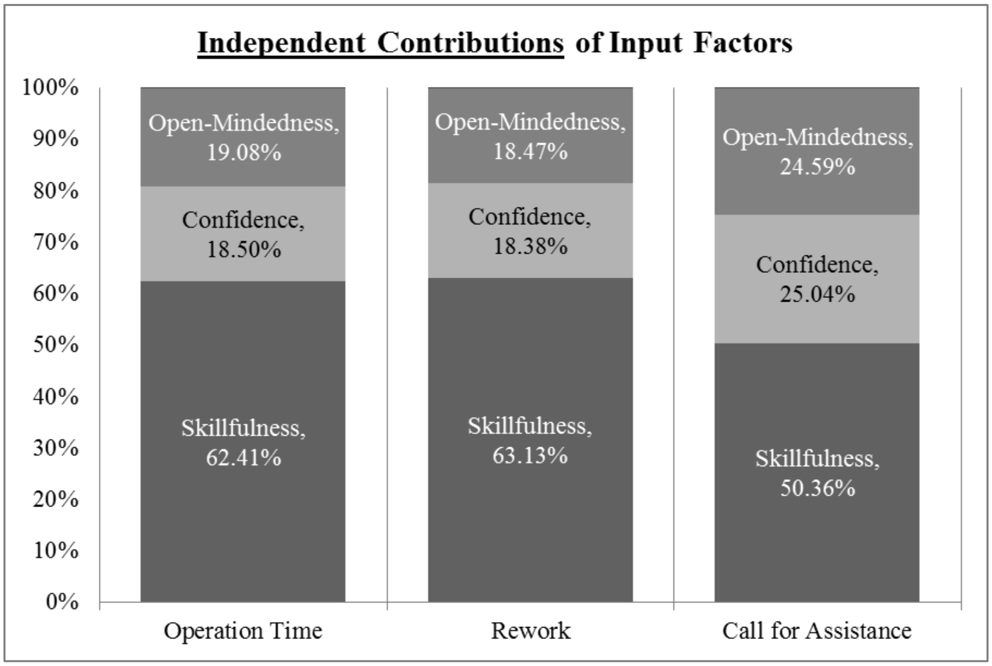


Figure 6.2 – Comparison of Independent Contributions of Input Factors with Respect to Outputs Variables

Open-mindedness, that is willingness of a work crew member to consider others' opinions, can be identified, based on the sensitivity indexes, as the next most-important factor in frequencies of call-for-assistance. It is of lesser impact on operation time, and is the least influential on causing rework and waste. A stubborn crew member may be seen, to insist, for example on her/his own interpretation of a cue which, depending on her/his skillfulness, can deviate from accuracy. That may cause rework, and lead to longer operation time/inefficient utilization of resources.

The confidence in ability, and reliability of a crew member seems to impose the least impact among the three factors for amount of rework and waste as the contributions of sensitivity indexes in Figure 6.2 reports. Confidence can be introduced as the next most-influential factor in frequency of call-for-assistance, and operation time/efficiency in resources utilization. It can be inferred that lesser confidence that a crew-mate will evaluate the situation appropriately and, when needed, will interpret a cue accurately increases the likelihood of call to the supervisor for assistance to seek (more) explicit directives. Greater level of confidence in crew-mate, on the other hand, contributes to a longer and less efficient operation time/resource utilization, and may also lead to some amount of rework depending on how skillful that crew-mate is.

These effects will be more meaningful and sensible when considered in combination with one another.

*Take-away*: Interactions between members of a homogeneous, in comparison with a heterogeneous, construction work crew results in outputs which may deviate less from expected ones.

The reality, however, is that a work crew is *what it is*! That is, with the fair assumption that members of a construction work crew are trained in a specific discipline, and are knowledgeable about *how-to* do their assigned activities, it is arguable that traits they bring to the crew will not change nor can it be altered. And as mentioned previously, exploratory and sensitivity analyses concluded that heterogeneity of such traits drives their interactions. Thus, it may be argued that those interactions may be directed towards positive influences. Lean Construction principles embodied in tools such as The Last Planner® System (LPS®) of Production Planning and Control may be named as appropriate means. As was referred to in Chapter Two Section (2.4), the LPS® mandates that an activity to be definable, sound, in sequence, and appropriately sizeable. LPS® declare soundness as a state in which every requirement an activity needs are available.

Soundness criteria can be particularly emphasized as important for two reasons: first – it ensures that directives an activity needs are present, explicit, and complete. Therefore, what-to do is clearly known and there will be minimal likelihood – if any – of cue interpretations. Second – it channels, directs, and focuses the interactions between crew members towards an advantageous output – i.e., making an activity ready for execution

Either it is in the make-ready stage or towards the weekly-work planning, two phases of LPS®, the soundness criteria unarguably minimizes ambiguity, and serves as a channel to effectively employ the inevitable interactions between crew members so implicitness is uncovered. In other words, it minimizes – if not eliminate – the iterative nature of cue interpretation illustrated in Figure 6.3, generation of waste, and inefficiency of operation.

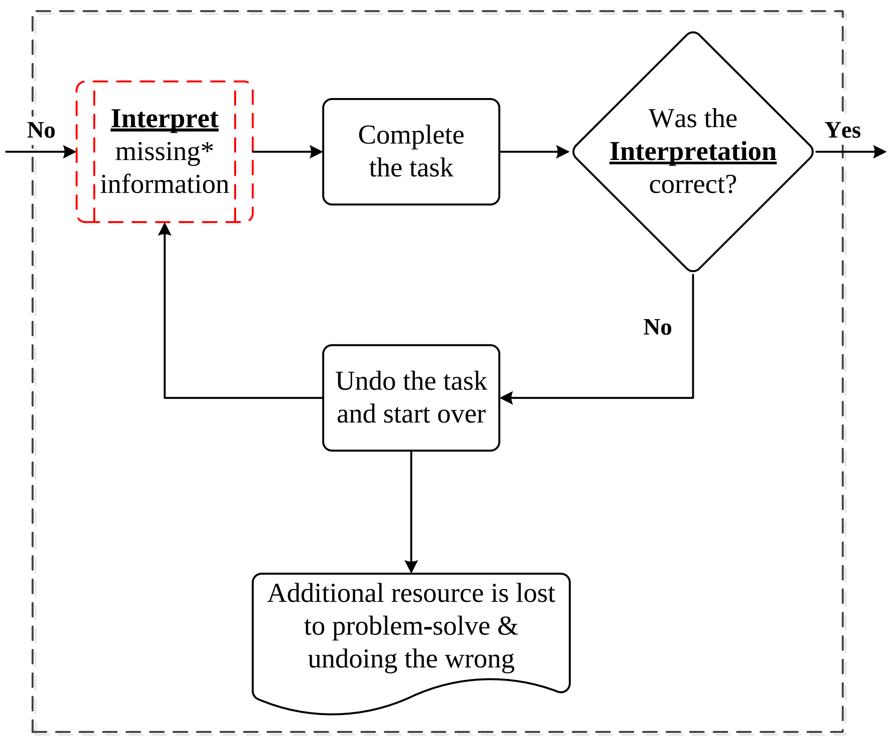


Figure 6.3 – Schematic Presentation of Iterative Process of Cue Interpretation
(i.e., adopted from Figure 4.2)

## (6.2) Contribution

Illustrated in Chapter Three Figure 3.1, contributions of this research dissertation to the body of construction-industry knowledge can be summarized as follows:

### Influential Factors on Cue Interpretation

Instrumenting a framework for qualitative interviews as Chapter Four discussed in details, fourteen implied factors were identified by construction skilled trade workers. These factors, summarized in Table 6.1, signified by one hundred and seventy six (176) construction work crew members as influential in ambiguous situations and where decisions are to be made in presence of cues and physical hints.

Table 6.1 – Frequency Analyses of Influencing Factors on Work Crew Members Interactions

| Influential Factor | Frequency of Implication |
|---|---|
| Knowledge and Skills | 22.1% |
| Confidence and Trust | 14.4% |
| Open-mindedness | 12.9% |
| Morale and Personality | 10.3% |
| Cost and Efficiency | 8.7% |
| Communication | 7.7% |
| Mutual Respect | 7.5% |
| Common Sense | 5.6% |
| Complexity of Task | 4.2% |
| Product Quality | 1.9% |
| Customer Satisfaction | 1.7% |
| Work Style | 1.4% |
| Collaboration | 0.8% |
| Feasibility of Solution | 0.7% |

Contents of qualitative interviews also implied that, as reported in Figure 6.4, crews were more eager to autonomously resolve such ambiguity and most-likely by discussing the issue with their crew-mates instead of contacting their supervisors, or customers.

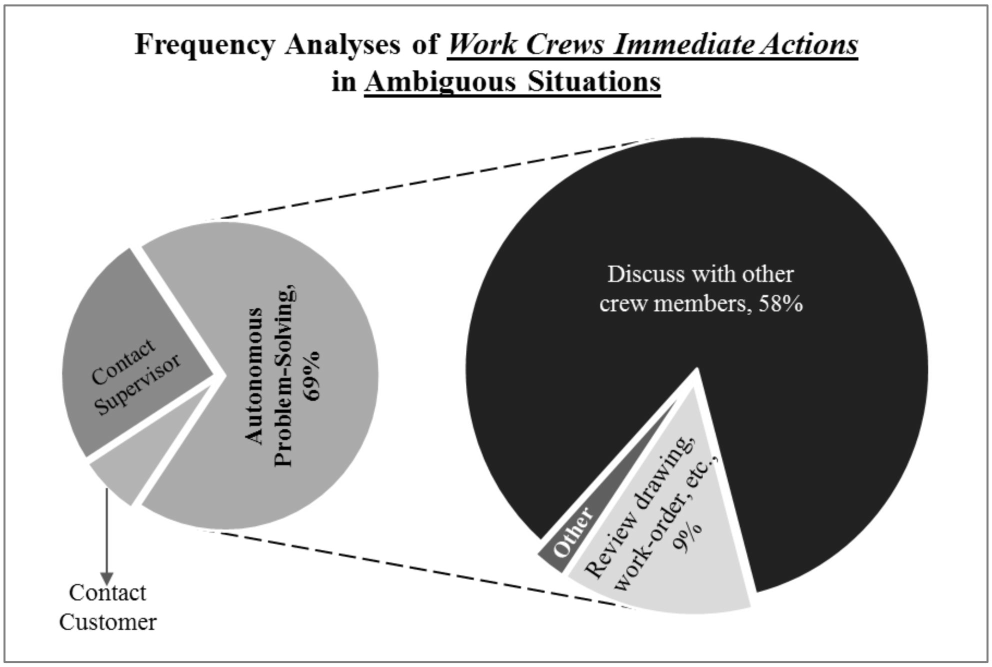


Figure 6.4 – Overall-Frequency Analyses of Work Crews Immediate Actions in Ambiguous Situations

<u>Conceptual Reference Framework of Cue Interpretation</u>

Presented in Chapter Four, a reference framework was developed to conceptually describe the phenomenon of cue-interpretation in a construction work crew. This conceptual framework was developed based on contents of qualitative interviews with 176 construction skilled trades workers. Concept of cue interpretation in construction job site and in absence of complete instruction and perfect information was introduced by Lahouti and Abdelhamid (2012).

Abstract Agent-based Model

This reference framework was then employed to develop an agent-based model in Chapter Five. The ABM was translated in programmable modeling environment of *NetLogo* (Wilensky, 1999); and was further developed to simulate dynamics (e.g., interaction) of a construction work crew to explore how interactions impact cue-interpretation. Sensitivity analyses of simulations outputs identified most-influential factors on interactions of crew members in case of cue-interpretation.

Overall Contribution

This investigation as a whole offers a computational validation of the quality-tasks concept, and constraint screening utilized in the Last Planner® System. The LPS® ability to prevent planning failures is undisputed given its mounting empirical evidence of the past quarter-century. The conclusion is that 'it works.' Why does it work has still not been adequately answered. This work has demonstrated a principled explanation that leads to a stronger understanding for why the LPS® works in maintaining reliable and predictable workflow on construction sites. The core of LPS® summarizes that:

(a) execution, and planning should not be separated; and

(b) projects are not scripted performance – rather, they are ongoing conversations.

In the absence of the routines and practices of the LPS®, the crew is not shielded from the damaging effects, of having to interpret cues and physical feature of workplaces as proven in this research. The cost is manifested in the delays caused by waiting for directive clarifications, and possibility of rework.

Moreover, this research dissertation provides a sound basis for crew member recruitment, and crew make-up. Skill is an intuitive requirement. However, it is worthwhile to interview and screen for the additional traits of confidence, and open-mindedness.

*Take-away*: Interaction between members of work crew is important in activity performance. Or in *"layman's terms"*, it is crucial for work crew to discuss and finalize its plan for action before start the task.

## (6.3) Limitation

With reference to Section (4.2) Figure 4.1 and from four types of inputs factors, which have been introduced in literature as influential on outputs of a work crew, only factors of type "individual" were modeled in the ABMS of this investigation. Such consequently assumes no influence or rather fixed contribution from other types of inputs factors – which indeed is a limitation of this investigation.

The literature relevant to small group research (to the extent surveyed in process of this investigation) did not define a unique mathematical representation for correlation between behavioral characteristics of group members. Therefore, a best-fit correlation was defined to describe interactions between two factors – Confidence and Open-mindedness. As Chapter Five Section (5.3) discussed the product (multiplication) was presented as an attempt of approximation in accordance with the literature best-fit approach.

Also discussed in Chapters Three and Five, real-life data was not available for factors introduced to ABMS; and therefore the simulation was executed with limited experiments designed based on probabilistically distributed values. Indeed future development of this research would benefit from distributions of collected data.

The potential artifact imposed by the specific layout of (developed) ABMS – graphically presented in Figure 3.2 and Figure 5.1 – can also be nominated as a limitation in this research. That is, although sensitivities of simulation outputs would be the same in ***quality*** to the input factors, their orders of magnitudes could be influenced by a specific layout.

## (6.4) Future Research

It was previously concluded that the attention of this investigation was directed towards interactions between members of a construction work crew as representation of a small group; and accordingly the Input-Process-Output (I-P-O) reference framework of Figure 4.1 was adapted from small group research literature to illustrate such interactions. It is believed by the researcher of this dissertation topic that Social Network Analysis (SNA) process of investigating social structures (e.g., a work crew) will enhance this work as SNA has the capabilities to shed lights on impacts of inputs factors on one another – one instance for the case of this research dissertation will be the impacts of interactions between input factors "Confidence and Trust" and "Open-mindedness" on variations in outputs.

As discussed in Chapters Three and Five, ABMS cycles did not represent the concept of *past experience*. In other words, agents did not have a *learning* attribute. $z$ simulation cycles presented $z$ groups of two agents each completed the same activity. Considering that an agent's confidence in another agent can be influenced by *past experience* – as is likely in a real-life situation – it will be a major development to correlate level of confidence with respect to decisions made by the corresponding agent. Enabling an agent to learn, and to carry-over its experience from one cycle to another was not within in the scope of this investigation; and is definitely a potential for future development.

Also mentioned in Chapter Five that visiting thirty two (32) neighbors to reach the destination (neighbor) exemplified the most efficient performance. Such conclusion was based on the assumption that visiting each neighbor (i.e., completing each tasks) would demand the same amount of time – in other words, different tasks were of equal durations. Relaxing such assumption will be a development for the future of this research in which different tasks will have completion time apportioned to their complexity.

**APPENDICES**

APPENDIX A: Framework for Qualitative Interview

*Decision-Making Process Heuristic among Construction Work Crew*

| **INTERVIEW GENERAL INFORMATION** | | |
|---|---|---|
| Number: _ _ _ _ _ _ | Date: _ _ _ _ _ _ | Venue: _ _ _ _ _ _ |

| **WORK CREW (ANONYMOUS) INFORMATION** | |
|---|---|
| Skilled Trade Discipline: _ _ _ _ _ _ _ _ _ _ _ | Current Title / Rank: _ _ _ _ _ _ _ _ _ _ _ |
| (Total) Number of Years of Experience: _ _ _ _ _ _ _ _ _ _ _ | Primary Category of Expertise: _ _ _ _ _ _ _ _ _ _ _ |
| Typical Structure of Work Crew: _ _ _ _ _ _ members _ _ _ _ _ _ + _ _ _ _ _ _ | |

***Situation:***
When you arrived on the job site, you realized that the situation did not match the instructions (e.g., construction drawing; verbal request; work-order; etc.) originally received; and you needed to acquire more information or informative instruction in order to complete your activity/task. In the meantime, there was a readily-available physical cue at the work face which might have – rightly or wrongly – filled in for the missing pieces of information:

| **DECISION-MAKING AT PRESENCE OF PHYSICAL CUE(S)** |
|---|
| Since you often work as a crew, how will you most likely respond / react to such a situation? _ _ _ _ _ _ _ _ _ _ _ |
| Will you please briefly elaborate? _ _ _ _ _ _ _ _ _ _ _ |
| Is there often an alternative task for you if your planned task cannot be completed? _ _ _ _ _ _ |

| EXAMPLE OF A DECISION-MAKING |
| --- |
| Activity Information: _ _ _ _ _ _ _ _ _ _ _ |
| Description of Situation:<br><br>_ _ _ _ _ _ _ _ _ _ _ |
| ‘WHAT’ did you do: _ _ _ _ _ _ _ _ _ _ _ |
| ‘HOW’ did you decide on the ‘WHAT’ to do?<br><br>_ _ _ _ _ _ _ _ _ _ _ |
| ‘WHY’ did you decide on that “WHAT’? _ _ _ _ _ _ _ _ _ _ _<br><br>Was that approach the best possible one: _ _ _ _ _ _ _ _ _ _ _ |
| How did the actual outcome of decision compare with the anticipated / expected result?<br>_ _ _ _ _ _ _ _ _ _ _ |

| MORAL OF THE STORY |
| --- |
| In your opinion, did ‘HOW’ [i.e., the process] you made a decision impose an impact on the task performance?<br>_ _ _ _ _ _ _ _ _ _ _ |
| What are the factors that have influenced [in descending order] ‘HOW’ you made decisions in similar situations [on operation level] in years of your experience on various projects?<br>_ _ _ _ _ _   _ _ _ _ _ _   _ _ _ _ _ _   _ _ _ _ _ _   _ _ _ _ _ _   _ _ _ _ _ _ |

| CRITICAL LESSEN(S) LEARNED / KEY TAKEAWAY(S) |
| --- |
| _ _ _ _ _ _ _ _ _ _ _ |

APPENDIX B: Agent-based Model

*NetLogo Programmable Environment Code*

```
To Setup
  No-Display
  Clear-All
  Clear-Patches
  Ask Patch 17 19 [Set pColor Red]
  Create-Turtles 1 [
    No-Display
    Set Call 0
    Set Color Blue
    Set Counter 0
    Set per-Level 0
    Set ReVisit [ ]
    Set ReWork [ ]
    Set Supervisor [ ]
    Set Step 0
    Set Visit [ ]
    Move-To Departure]
  Display
  Reset-Ticks
End

To Find-Shortest-Path-to-Destination
  Set Path Find-A-Path Patch-Here Patch X Y
  Set Optimal-Path Path
  Set Current-Path Path
End

To-Report Find-a-Path
[Short-Departure Short-Destination]
  Let Search-Done? False
  Let Search-Path [ ]
  Let Current-Patch 0
  Set Open [ ]
  Set Closed [ ]
  Set Open lPut Short-Departure Open
  While [Search-Done? != True ]
  [IfElse Length Open != 0
    [Set Open Sort-By [[F] of ?1 < [ F ] of ?2 ] Open
```

```
    Set Current-Patch Item 0 Open
    Set Open Remove-Item 0 Open
    Set Closed lPut Current-Patch Closed
    Ask Current-Patch
    [IfElse Any? Neighbors4 with [(pXCor = [pXCor] of Short-Destination) And (pYCor = [pYCor] of Short-Destination)]
     [Set Search-Done? True]
     [Ask Neighbors4 with [pColor != Black And (Not Member? Self Closed) And (Self != Parent-Patch)]
      [If Not Member? Self Open And Self != Short-Departure And Self != Short-Destination
       [Set Open lPut Self Open
        Set Parent-Patch Current-Patch
        Set G [G ] of Parent-Patch + 1
        Set H Distance Short-Destination
        Set F (G + H)]]]]]
   [User-Message ( "No Patch Exists !" )
    Report [ ]]]
 Set Search-Path lPut Current-Patch Search-Path
 Let Temp First Search-Path
 While [Temp != Short-Departure]
 [Ask Temp
  [Set pColor 2]
  Set Search-Path lPut [Parent-Patch] of Temp Search-Path
  Set Temp [Parent-Patch] of Temp]
 Set Search-Path fPut Short-Destination Search-Path
 Set Search-Path Reverse Search-Path
 Report Search-Path
End
```

**To Re-Run**

```
 Set Color Blue
 Set Heading One-of [0 90 180 270]
 Set ReVisit [ ]
 Set Step 0
 Set Visit [ ]
 Move-To Departure
End
```

**To Factor-Confidence-&-Trust**

```
 Set Confidence-Trust [ ]
 ForEach (n-Values Crew-Size [? + Crew-Size])
 [Set Confidence-Trust lPut Confidence-Trust Confidence-Trust]
End
```

**To Factor-Knowledge-&-Skill**

```
 Set Current-MoveTo-Patch [ ]
```

```
  Set MoveTo-Patch-Crew [ ]
  Set Crew ( n-Values Crew-Size [1] )
  Set Current-Knowledge-Skills [ ]
  Set Knowledge-Skill [ ]
  ForEach (n-Values Crew-Size [?])
  [Set Knowledge-Skill lPut Knowledge-Skill Knowledge-Skill]
    Repeat Crew-Size [
  Let Temporary-Knowledge-Skills (Random-Float 1)
  Set Current-Knowledge-Skills Sentence Current-Knowledge-Skills Temporary-Knowledge-Skills]
  ForEach Current-Knowledge-Skills
  [IfElse ? > (Item (Position ? Current-Knowledge-Skills) Knowledge-Skill)
    [Let Index (Position ? Current-Knowledge-Skills)
      Find-Available-Patch
      Find-HeadingTo-Patch
      If Empty? Current-MoveTo-Patch
      [Set Current-MoveTo-Patch "N/A"
        Set Crew Replace-Item Index Crew (10 ^ 3)]
      Set MoveTo-Patch-Crew Sentence MoveTo-Patch-Crew Current-MoveTo-Patch]
    [Set MoveTo-Patch-Crew Sentence MoveTo-Patch-Crew (Item 1 Optimal-Path)]]
End
```

**To Factor-Open-Mindedness**

```
  Set Open-Mindedness [ ]
  ForEach (n-Values Crew-Size [? + (Crew-Size * 2)])
  [Set Open-Mindedness lPut (Item ? Factor-Data) Open-Mindedness]
End
```

**To Find-Available-Patch**

```
  Set Available [ ]
  Set Current-MoveTo-Patch [ ]
  Set Neighbor [0 90 180 270]
  Set Sign [ ]
  Set Target [ ]
  ForEach Neighbor
  [IfElse NoBody = Patch-At-Heading-And-Distance ? 1
    [Set Neighbor Remove ? Neighbor]
    [If (Black != [pColor] of Patch-At-Heading-And-Distance ? 1)
      [Set Available Sentence Available ?]]]
  ForEach Available
  [IfElse Member? (List [pXCor] of Patch-At-Heading-And-Distance ? 1 [pYCor] of Patch-At-Heading-And-Distance ? 1) Visit
    [Set Available Remove ? Available]
    [If Red = [pColor] of Patch-At-Heading-And-Distance ? 1
      [Set Target Sentence Target Patch-At-Heading-And-Distance ? 1
        Set Current-MoveTo-Patch Target]
```

```
    If (Green = [pColor] of Patch-At-Heading-And-Distance ? 1 And Empty? Target)
    [Set Sign Sentence Sign Patch-At-Heading-And-Distance ? 1
     Set Current-MoveTo-Patch Sign]]]
  ForEach Available
  [Set Available Replace-Item (Position ? Available) Available Patch-At-Heading-And-Distance ?
1]
End
```

**To Find-HeadingTo-Patch**

```
  If (Empty? Current-MoveTo-Patch And Not Empty? Available)
  [Set Current-MoveTo-Patch (List One-of Available)]
   If (Empty? Current-MoveTo-Patch And Empty? Available)
  [Escape-Dead-End]
End
```

**To Log-Visit-Patch**

```
  Let Location (List ([pXCor] of Patch-Here) ([pYCor] of Patch-Here))
  If (Member? Location Visit And Not Member? Location ReVisit)
  [Set ReVisit Sentence ReVisit (List Location)]
  Set Visit Sentence Visit (List Location)
  Set Visit Remove-Duplicates Visit
End
```

**To Escape-Dead-End**

```
  Set Available [0 90 180 270]
  ForEach Available
  [IfElse (NoBody = Patch-At-Heading-And-Distance ? 1
    Or Black = [pColor] of Patch-At-Heading-And-Distance ? 1
    Or Member? (List [pXCor] of Patch-At-Heading-And-Distance ? 1 [pYCor] of Patch-At-
Heading-And-Distance ? 1) ReVisit)
   [Set Available Remove ? Available]
   [Set Current-MoveTo-Patch Sentence Current-MoveTo-Patch Patch-At-Heading-And-Distance
? 1]]
  If (Length Current-MoveTo-Patch > 1)
  [Set Current-MoveTo-Patch (List One-of Current-MoveTo-Patch)]
End
```

**To Contact-Supervisor**

```
  Set Call Call + (1)
  Log-Visit-Patch
  Set Departure Patch 3 1
  Set Visit [ ]
  Move-To Departure
End
```

**To Apply-Factors**

```
  Factor-Knowledge-&-Skill
  Factor-Confidence-&-Trust
  Factor-Open-Mindedness
  Aggregate-Factors
End
```

**To Aggregate-Factors**

```
  Set Performance-MoveTo-Patch-Crew [ ]
  Set Performance-MoveTo-Patch-Crew Remove-Duplicates MoveTo-Patch-Crew
  Let Weight (Map [?1 * ?2 * ?3 ] Crew Confidence-Trust Open-Mindedness )
  Set Move-Factors [ ]
  Set MoveTo-Patch-Crew (List (Item (Position (Max Weight) Weight) MoveTo-Patch-Crew))
  Set MoveTo-Patch-Crew (List (Item (Position (Min Weight) Weight) MoveTo-Patch-Crew))
  Set MoveTo-Patch-Crew Remove "N/A" MoveTo-Patch-Crew
  ForEach (List Position ( Min Weight ) Weight )
  [Set Move-Factors lPut Item ? Knowledge-Skill Move-Factors
    Set Move-Factors lPut Item ? Confidence-Trust Move-Factors
    Set Move-Factors lPut Item ? Open-Mindedness Move-Factors]
End
```

**To Move**

```
  IfElse Empty? MoveTo-Patch-Crew
  [Contact-Supervisor]
  [Measure-Performance
    Move-To One-of MoveTo-Patch-Crew
    Set Step Step + (1)]
    ForEach Optimal-Path
    [If (Position ? Optimal-Path) > 0 And (Position ? Optimal-Path) < (Length Optimal-Path - 1)
      [Ask ?
        [Set pColor White]]]
End
```

**To Count-A-Move**

```
  Set Collect-Step Sentence Collect-Step Step
  Set per-Level per-Level + 1
  IfElse (per-Level = Iteration)
  [Let M-Move Max Collect-Step
    Let N-Move Round Mean Collect-Step
    Let R-Move Length ReVisit
    Set Average Sentence Average N-Move
    Set Supervisor Sentence Supervisor Call
    Set Maximum Sentence Maximum M-Move
    Set ReWork Sentence ReWork R-Move
    Set Collect-Step [ ]
    Set Counter (Counter + 1)
    Set Call 0
```

```
    Set per-Level 0
    Set Performance [0 0 0 0]
    Re-Run]
  [Re-Run]
End
```

**To Make-Decision**

```
  Ask Turtles
  [IfElse Patch-here = Destination
    [Count-A-Move]
    [Log-Visit-Patch
      Find-Shortest-Path-to-Destination
      Apply-Factors
      Move]]
  Tick
End
```

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