Crew Coordination Modeling in Wood-Framing Construction

by

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ABSTRACT

The wood-framing trade has not sufficiently been investigated to understand the work task sequencing and coordination among crew members. A new mental framework for a performing crew was developed and tested through four case studies. This framework ensured similar team performance as the one provided by task micro-scheduling in planning software. It also allowed evaluation of the effect of individual coordination within the crew on the crew's productivity.

Using design information, a list of micro-activities/tasks and their predecessors was automatically generated for each piece of lumber in the four wood frames. The task precedence was generated by applying elementary geometrical and technological reasoning to each frame. Then, the duration of each task was determined based on observations from videotaped activities. Primavera's (P6) resource leveling rules were used to calculate the sequencing of tasks and the minimum duration of the whole activity for various crew sizes. The results showed quick convergence towards the minimum production time and allowed to use information from Building Information Models (BIM) to automatically establish the optimal crew sizes for frames.

Late Start (LS) leveling priority rule gave the shortest duration in every case. However, the logic of LS tasks rule is too complex to be conveyed to the framing crew. Therefore, the new mental framework of a well performing framer was developed and tested to ensure high coordination. This mental framework,

based on five simple rules, can be easily taught to the crew and ensures a crew productivity congruent with the one provided by the LS logic.

The case studies indicate that once the worst framer in the crew surpasses the limit of 11% deviation from applying the said five rules, every additional percent of deviation reduces the productivity of the whole crew by about 4%.

In memory of my grandparents Florian and Ilona, who are the motivational leaders and role models in my life.

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TABLE OF CONTENTS

CHAPTER Page

CHAPTER Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Chapter 1

INTRODUCTION

1.1 Statement of Purpose

Maximizing the performance of a wood-framing construction team at the job site depends to some extent on the performance of individuals. This research endeavor aims to produce a better understanding of effective and adaptive team behavior in the field of wood-framing construction. The deliverable product aims to fit individual skill with team task for structuring adaptive teams. Two characteristics shared by effective teams are a nonverbal communication of a final product in the form of a mental model and an unspoken sequence of procedures. Clear-cut teamwork has potential to improve all three areas of performance: productivity, safety, and quality.

In the taxonomy of sciences, this study can be placed on the border between stochastic and rule-based modeling. The broader impact of this study will be the production of team-skills taxonomy within the different trades. Integration of team skills to improve work practices and situation awareness is the main research goal. The useful final product aims to provide training insights for structuring adaptive teams that are better matched with the type of work required in their respective trade.

1.2 Statement of Objective

Unlike employees at a manufacturing plant, construction field workers have few repetitive tasks. There is mounting evidence (Salas, Cooke and Rosen, 2008) from the cognitive engineering sciences that group work requires a different skill-set than individual performance. However, it is arguable that similarities in mental models acquired during individual work are crucial for achieving a high performance team. For example, the Australia national rugby team has had a touring segment known as the Kangaroos. The 1982 Kangaroos were the first touring team to go unbeaten in twenty-two games despite having no individual superstars (Wikipedia, 2011). In fact, it appears that the players had nothing but a compact set of skills: pace, guile, teamwork, and fitness. For this research, it is assumed that clear-cut teamwork has the potential to improve a crew's performance. The specific question this research is aiming to answer is: how do we fit individuals to a specific wood-framing construction team to ensure a high level of performance?

There are several reasons why this question has not been answered earlier. Wood-framing is a dynamic activity, in which both the object of the work (the goal) and the location are changing many times a day. Capturing the performance of such dynamic teams is a challenging investigation. Consequently, the body of knowledge on team formation and development in the construction industry is deficient. The study requires a cross-disciplinary approach ranging from construction objects and methods modeling to productivity measurement through motion study, and team cognition modeling. Each of the disciplines required further development to allow the completion of this particular study.

1.3 Major Productivity, Safety and Quality Issues in Wood-Framing Construction

Wood framing construction can be classified into the following areas: tools and materials, rough carpentry, exterior finish, and interior finish. For tools and materials, there are the following main categories: wood and lumber, engineered panels (rated plywood and panels, nonstructural panels), engineered lumber products (LVL, PSL and LSL, wood I-joists, glue-laminated lumber), fasteners (nails, screws, anchors, etc.), hand tools (boring and cutting tools, fastening, layout tools), portable power tools (saws, drills, drivers, fastening tools), and stationary power tools (circular saw blades, radial arms and miter saws, table saws). The breakdown for rough carpentry includes: building layout, concrete forms, floors, exterior walls, interior rough work, scaffoldings, roof framing, stairs, insulation and ventilation. Breakdown for exterior finish carpentry includes: roofing, windows, exterior doors, sidings, decks, porches and fences. Interior finish carpentry classification includes drywall construction, wall paneling, ceiling finish, interior doors and door frames, interior trim, stair finish, finish floors, cabinets and countertops. The tasks that compose these building products come in their execution with various demands that need to be accomplished to get finally the products that will constitute parts of the residential or commercial building.

The major productivity issues that interfere with the work associated with individual tasks or assemblies that enter these products are: weather variability, lack of experience, inadequate materials, numerous position changes, ineffective communication, inadequate planning and scheduling of the work, lack of coordination between framers and poorly designed tools. Research shows that labor effectiveness is a combined measure of factors such as motivation, training (rules and behaviors), perceived feedback, physical limitations and cognitive measures of the performed tasks (skills, capabilities and interpersonal relations).

The analysis of accidents in wood-framing (Mitropoulos and Guillama, 2010) revealed most factors that determine the difficulty of framing tasks, like working on platform constraints, ergonomic postures constraints (bending, extending the body, etc.), material/load handling requirements, tool use/accuracy requirements and difficulties due to external forces (e.g. wind-important in roof tasks, coordination between framers when lifting walls). The majority of accidents are classified in this industry under the following categories: falls (falls from ladders), trip/slips, nail gun punctures, stepped on, foreign body (splinter/eye debris), hit by/against, and strains. There are certain safety interventions that can reduce the task difficulties and the frequency of incidents while at the same time improving the productivity of the whole activity.

Currently, the wood-framing industry is focused on streamlining the construction process, resulting in too little time and attention spent on the details that sometimes are critical in obtaining a finished product consistent with quality construction goals and standards. There are likely additional costs associated with this initiative, although in the long term, cost savings arising from improved framing practice may offset the additional installation labor and third-party inspections costs.

Framing is one of those products in which once a minimal required quality is achieved, better quality adds no value to the final product (residential or a commercial buildings). The minimal quality is ensured through quality checks performed by the framers or foremen, as described below. The lumber is checked before the work starts. Framers usually have 24 hours to send back wrong material, which they call “cull” lumber. Cull lumber is replaced with new, straight material. The concrete slabs may have high and low spots that affect the quality of framing. Foremen state that when they have issues with the concrete at bearing wall locations, they call the tract superintendent and have the concrete company send a crew to fix the slab. As soon as they start framing on the slab, they take full responsibility for it. A comprehensive list of quality checks for wall framing and roof framing, as discussed with foremen on the jobsite, can be found in Appendix A.

Even though the quality issues are not considered throughout the current study, it is important to understand that these checks can have serious implications in the outputs of the work and the effectiveness of the wood-framing crews if they are carried out during the actual construction time.

1.4 Intellectual Merit and Broader Impact

The results of the research provide an objective measurement of the individual’s contribution to the success of a team, thus allowing a broader integration of people in construction, regardless of gender or stature. The research is:

- providing new capabilities for analysis of framing operations through an innovative methodology and analysis;
- describing with accuracy the team mental model and procedures to the final outcome to achieve high-performance teams;
- through an accurate team mental model, fitting individual skill with team task for structuring adaptive teams.

Capturing and creating an accurate mental model of performing crews in construction trades enable the systematic development of effective, stable and resilient production systems. This aspect has a significant impact on how the industry selects and trains field personnel and organizes the work to be more productive, based on the output sought. At the same time, activities developed based on these research results will be less prone to errors and to accidents. Therefore, the main goal of this research is to generate significant social and economic benefits to the industry and to have an impact over other disciplines, relinquishing a new body of knowledge about modeling coordination and interaction in crews (construction teams).

1.5 Problem Statement

The literature review presented in the next chapter reveals that the effectiveness of a wood-framing crew depends on the performance of each individual and on “the way” they work together. The researcher is assuming also that two “silent” characteristics are shared by effective teams:

(1) shared mental model (SMM) of the final product (or “what needs to be built?”- a specific frame, in this case) and

(2) the sequence of tasks performed by each crew member (or "how is the frame going to be built?")

The broader aim of this research is to fit individual skill with team task for structuring effective construction crews in each known trade. Table 1 was compiled with the intent of identifying the major construction trades in which this study may have applicability.

Table 1. Construction Trades and Code Identification

TRADE/Description of work	Code
Brick masons, block masons, and stonemasons	Br
Carpet, floor, and tile installers and finishers	Cr
Cement masons, concrete and terrazzo finishers	Cn
Construction equipment operators	Op
Drywall installers	Dr
Electricians	El
Glaziers	Gl
Insulation workers	In
Ironworkers	Ir
Painters and paperhangers	Pa
Plasterers and stucco masons	Pl
Plumbers, pipelayers, pipefitters, steamfitters	Pm
Roofers	Rf
Sheet metal workers	Sh
Tile setters and marble setters	Ti

However, this particular research focuses only on wood framing. Relevant to this wood-framing processes study, there are two research questions to answer:

1. How do teams or crews solve problems together? In other words how do they become aware of a particular situation as a group, how do they share information/situations and make decisions as a unit?

2. What roles does individual performance play in the performance of the whole crew?

Chapter 2

A REVIEW OF LITERATURE CRITICAL TO RESEARCH

2.1 Long-Range Productivity Studies - Team Factors, Team Situation Awareness and Crew Resource Management (CRM)

Garay and Guillermo (2006) showed how poor comprehension of Situational Awareness (SA), lack of CRM knowledge transferred into skills, and a poor understanding of Human Factors (HF) concepts can rapidly change a situation from normal to highly dangerous without team members becoming aware of the change. Their paper shows how such a risky situation can be easily avoided and managed safely just by applying some well established rules.

Cooke, Salas, Cannon-Bowers and Stout (2000) describe how multioperator tasks often require complex cognitive processing at the team level. Team knowledge is many-sided and comprised of generic knowledge in the form of team mental models and more specific, team situation models. The authors' methodological review paper and recent efforts to measure team knowledge is reviewed in the context of mapping specific methods onto features of targeted team knowledge.

Gorman, Cooke and Winner (2006) emphasize that decentralized command and control settings like those found in the military are "*prevalent with complexity and change.*" These settings typically involve dozens, if not hundreds to thousands, of heterogeneous players coordinating in a distributed fashion within a dynamically networked battlefield that is burdened with sensor data, intelligence reports, communications, and plans emanating from many different perspectives. Considering the concept of team situation awareness (TSA) in this setting, the researcher attempted to answer these questions:

- What does it mean for a team to be aware of a situation or, more importantly, of a critical change in a situation?
- Is it sufficient or necessary for all individuals on the team to be independently aware of a situation?
- Or is there some more holistic awareness of a situation that emerges as team members interact?

The researchers re-examine the concept of team situation awareness in decentralized systems beyond an individual-oriented knowledge-based construct by considering it a team interaction-based phenomenon. A theoretical framework for a process-based measure called "coordinated awareness of situations by teams" (CAST) is outlined in this work. The paper presents a theoretical basis for measuring TSA in decentralized command and control environments using the basic components of CAST measurements. New issues are addressed with implications concerning team cognition, TSA theory, measurement, training, and design.

Zsambok, Klein, Kyne and Klinger's research (1992) describes the Advanced Team Decision Making (ATDM) model along with an application of a case study in military teams. Based on their observations of numerous tactical and strategic decision making teams, they derived three key components of advanced team decision making: team self identity, team conceptual level, and team self monitoring. The model contains ten key behaviors critical to team development in these components. As a result of their observations, the researchers identified the *critical* behaviors among hundreds of teams' behaviors which distinguished the high performance teams from less productive ones. Therefore, they developed an ATDM model based on these critical behaviors.

2.2 Cognitive Engineering Studies – Shared Mental Models and Team Interaction

Shared Mental Models (SMM)

Waller, Gupta and Giambatista (2004) associate control crews as highly trained teams responsible for monitoring complex systems, performing routine procedures, and quickly responding to non-routine situations. Previous literature cited in their paper suggests that higher performing control crews engage in adaptive behavior during high-workload or crisis situations. Other work suggests that higher-performing crews use periods of lower workloads to prepare for future problems. To understand which behaviors performed during which situations better differentiate lower from higher performing crews, the authors conducted a study of 14 nuclear power plant control room crews and examined adaptive behaviors and shared mental model development in the crews as they faced monitoring, routine, and non-routine situations.

One of the findings of this study was that lower performers engaged in more information collection across workload conditions than did the higher performers. The findings suggest that for control crews in dynamic environments, the occurrence of a non-routine problem might be an important boundary condition. This situation affects the influence of information collection on crew performance. A second important finding was the ability of higher performers to collect information and develop shared mental models during non-routine situations. This might be indicative of a crew's multi-tasking ability in general.

The results suggest that few differences in adaptive behaviors exist between higher and lower performing crews during monitoring or routine situations. During non-routine situations, information collection, shared mental model development activities, and inner-crew processes used during model development, differ significantly between lower and higher performing control crews in a non-routine situation.

Cooke and Durso (2008), reporting work done by Klinger and colleagues, presented an interesting study bringing out the effects of interventions on the performance of a large-scale emergency team in a nuclear power plant. The exercise of successive drills revealed that performance improves over a number of drills when staff size decreases. Also, they suggested that one cannot underestimate the value of skilled observers and their abilities to help an organization diagnose and repair its own weaknesses (decision-making experts).

Langan-Fox, Anglim and Wilson (2004) present us with a number of difficulties regarding the concept of team mental models, specifically: *incompleteness, multiplicity, and inconsistency*. Not the least of these difficulties is the problem of "capturing" (measuring) mental models, and still more difficult, capturing a team mental model, an extension of the earlier term. Their research paper tries to describe an analytic procedure to analyze team mental models.

Mohammed, Klimoski and Rentsch’s (2000) research searches to *promote the advancement of empirical research on team mental models* by:

- highlighting the conceptual work that must precede the selection of any measurement tool
- delimitating measurement standards for group-level cognitions
- evaluating a set of techniques for measuring team mental models

Because team mental models are extremely complex variables, multiple measures are required for a thorough assessment. The authors suggest that researchers should be aware of conclusions that rest on the use of a single method. Therefore, it is unlikely that team-related outcomes can be predicted effectively except by combining the strengths of different techniques. Furthermore, across the different techniques, it would be worthwhile to conduct studies in which both global and aggregated measurement techniques are used to compare the resulting team mental models for similarities and differences.

Carley and Palmquist (1992) describe how in making decisions or talking to others, people use mental models of the world to evaluate choices and frame discussions. Their study describes a methodology for representing mental models as maps, extracting these maps from texts, and analyzing and comparing these maps. The methodology employs a set of computer-based tools to analyze written and spoken texts. These tools support textual comparison both in terms of what concepts are present and in terms of what structures of information are present. The methodology supports both qualitative and quantitative comparisons of the resulting representations. This approach is illustrated using data drawn from a larger study of students learning to write, in which it is possible to compare mental models of the students with those of the instructor.

Nemire (2008) suggested that mental models are internal representations of the external world thought *to influence perception and decision-making.* An inappropriate mental model of a "roller coaster" was hypothesized to have caused the injury of one person and the death of another in a roller coaster incident. A study was conducted to learn about existing internal representations of roller coasters. Participants were asked to draw a roller coaster. Despite the existence of several types of roller coasters, 98% of the study participants drew a roller coaster representing the oldest and most prevalent type of coaster. The results of the study demonstrate that the internal representations were incomplete and penurious with respect to this injury incident; this shows the importance of educating product users about more appropriate mental models that may help prevent injury or death. Finally, it is suggested that training can correct deficiencies in mental models, and therefore enhance performance by providing more complete and accurate details and processes for the system being represented.

2.3 Safety Studies

Mental Workload

The research of Rubio, Diaz, Martin and Puente (2004) evaluates several psychometric properties (intrusiveness, sensitivity, diagnosticity, and validity) of three multidimensional subjective workload assessment instruments: the NASA Task Load Index (TLX), the Subjective Workload Assessment Technique (SWAT) and the Workload Profile (WP). The analysis of mental workload in a certain job leads to a number of practical implications for the training plans, the selection process, and task designing and redesigning. A major goal of work psychology is the analysis of task demands in order to design jobs that bring about a lower mental workload. This in turn is leading to lower stress levels and accident rates and to a decrease in the likelihood of errors as well, hence, the importance of mental workload evaluation.

This research attempted to analyze and compare the characteristics of three measures of subjective mental workload: NASA-TLX, SWAT and WP.

Subjects accepted willingly the three instruments although there were some problems concerning comprehension of the dimensions in the WP. As for the SWAT, the ranking task prior to the performance of the experimental tasks proved wearisome. To sum up, some basic recommendations can be given concerning the evaluation of mental workload in applied settings, depending on the goals:

- If the goal is a comparison between the mental workload of two or more tasks with different objective levels of difficulty, then the assessor should choose the Workload Profile.
- If the goal is to predict the performance of a particular individual in a task, then NASA-TLX is recommended.
- If what is needed is an analysis of cognitive demands or attention resources demanded by a particular task, then the best choice would be WP or, as an alternative, SWAT.

Workload Measures

1. *The NASA Task Load Index* (Hart and Staveland, 1988) uses six dimensions to assess mental workload: mental demand, physical demand, temporal demand, performance, effort, and frustration. Table 2 shows the definitions of NASA-TLX dimensions.

Table 2. Rating Scale Definitions and Endpoints from the NASA Task Load Index

TITLE	ENDPOINTS	DESCRIPTIONS
MENTAL DEMAND	Low/High	How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	Low/High	How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	Low/High	How much time pressure did you feel due to the rate or pace at which the task or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter? How satisfied were you with your performance in accomplishing these goals?
EFFORT	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	Low/High	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

2. *The Subjective Workload Assessment Technique –SWAT* (Reid and Nygren, 1988) is a subjective rating technique that uses three levels: (1) low, (2) medium, and (3) high, for each of the three dimensions of time: load, mental effort load and psychological stress load, which is used to assess workload. Table 3 shows the SWAT rating scale dimensions.

Table 3. Subjective Workload Assessment Technique (SWAT) Rating Scale dimensions

I. Time Load	
1.	Often have spare time. Interruptions or overlap among activities occur infrequently or not at all.
2.	Occasionally have spare time. Interruptions or overlap among activities occur infrequently.
3.	Almost never have spare time. Interruptions or overlap among activities are very frequent, or occur all the time.
II. Mental Effort Load	
1.	Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention.
2.	Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainly, unpredictability, or unfamiliarity. Considerable attention required.
3.	Extensive mental effort and concentration are necessary. Very complex activity requiring total attention.
III. Psychological Stress Load	
1.	Little confusion, risk, frustration, or anxiety exists and can be easily accommodated.
2.	Moderate stress due to confusion, frustration, or anxiety noticeably adds to workload. Significant compensation is required to maintain adequate performance.
3.	High to very intense stress due to confusion, frustration, or anxiety. High extreme determination and self-control required.

3. *Workload Profile (WP).* Tsang and Velazquez (1996) have introduced and evaluated a new multidimensional instrument to assess subjective mental workload, based on the multiple resource model of Wickens (1987). Their instrument, Workload Profile, tries to combine the advantages of secondary task performance based procedures (high diagnosticity) and subjective techniques (high subject acceptability and low implementation requirements and intrusiveness). As Tsang and Velazquez recognizes, the Workload Profile technique needs more detailed and extensive research about its properties. The Workload Profile asks the participants to provide the proportion of attentional resources used after they had experienced all of the tasks to be rated. The tasks to be rated are listed in a random order down the column and the eight workload dimensions are listed across the page (Table 4). The workload dimensions used in

this technique can be defined by the resource dimensions hypothesized in the multiple resource model of Wickens (1987): perceptual/central processing, response selection and execution, spatial, processing, verbal processing, visual processing, auditory processing, manual output, and speech output. Participants have available to them the definition of each dimension at the time of the rating. In each cell on the rating sheet, participants provide a number between zero and one to represent the proportion of resources used in a particular dimension for a task. A rating of "zero" means that the task placed no demand on the dimension being rated; a rating of "one" means that the task required maximum attention. The ratings on the individual dimensions are later summed for each task to provide an overall workload rating.

Table 4. Workload Profile Rating Sheet

Workload Dimensions								
	Stage of processing		Code of processing		Input		Output	
Task	Perceptual/ Central	Response	Spatial	Verbal	Visual	Auditory	Manual	Speech
m2								
m2s1								
m2s3								
m4								
m4s1								
m4s3								
s1								
s3								

There is also valuable research performed on emergency response teams for various industries (naturalistic decision making in a wide variety of task domains and settings, including firefighting, aviation, market research, command

and control, software troubleshooting, etc.). In this sense, Klinger and Klein (1999) demonstrated how application of a team training model can be the key to the increased efficiency of an emergency response team in the nuclear power plants. Their premise was that applying skills in the areas of macro-ergonomics and cognitive engineering would be effective, even in the absence of domain knowledge. They also showed an interesting curvilinear effect of increasing staff size on workload based on the ratio of real work to the time spent in managing information flow. To boost team performance and improve its functioning, it was necessary to downsize the personnel working for the organization responding to an emergency case. There were numerous changes made relevant to team functioning in addition to the decrease in team size. Decreasing size in the original (poorly designed) system would have likely hurt performance.

2.4 Coordination and Strategy Formation in Organizations

Mintzberg (1978) broadens the definition of strategy from a preconceived intentional plan to a “pattern in a stream of decisions.” Both “intended” and “realized” strategies can be studied within a complex dynamic surrounding and bureaucratic impetus by using this expanded definition. An intended strategy is precise and made in advance. A realized strategy is conceived over time. It is a “pattern in a stream of decisions” (p. 935). Accepting both types of strategic formation enables researchers to consider both prior and evolved approaches.

Exploratory research was conducted to detect the development and breakdown (change) of patterns over time. Four steps were followed: “collection of basic data, inference of strategies and periods of change, intensive analysis of periods of change, and theoretical analysis" (p. 936). In the first step, interviews were conducted and newspaper reports, product catalogs, and meeting minutes were analyzed in chronological order. Patterns during periods of change were then marked as incremental, piecemeal, global, continuity, limbo, or flux. The data were then more intensively scrutinized. The last step identified when a decision was "proactive or reactive" (p. 936). Two case studies, Volkswagenwerk and Vietnam, were reported using the codification for patterns in strategic decision-making.

Organizational strategies form around the interchange of three forces: environment, bureaucracy, and leadership. "A strategy is not a fixed plan, nor does it change systematically at pre-arranged times solely at the will of management" (p. 947). Most of the studies depicted two main patterns based on life cycle and waves of change brought on by force interplay. Most bursts of change were followed by a stage of stability.

The researchers take "intended" and "realized" strategies one-step further by combining them in three ways. The conceptual framework of strategy types best communicates "deliberate" versus "emergent" strategies (p. 945) (Figure 1):

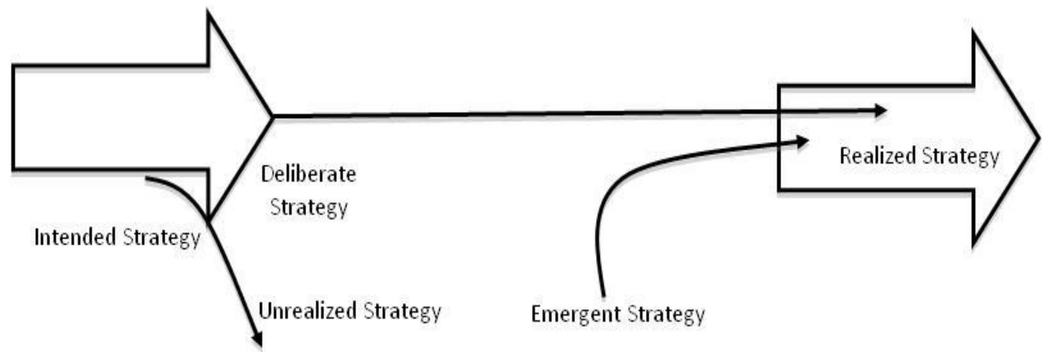

Figure 1. Types of strategies

Deliberate strategies are “intended strategies that get realized” (p. 945). Intended strategies that do not get carried out are unrealized strategies. Emergent strategies get realized even thought they were never proposed at the onset.

In summary, Mintzberg expresses that strategies are molded by the interface of three forces: environment, bureaucracy, and leadership. They are either intended or realized. Patterns in the chronological flow of decision-making can be codified as incremental, piecemeal, global, continuity, limbo and flux. Organizations become proactive or reactive and strategies are unrealized, deliberately realized, or unintentionally realized (emergent).

Mintzberg (1980) provides five part lists for organizations, mechanisms of coordination, structural configurations, decision-making systems and contingency factors.

<u>5 parts of an organization:</u>

1. Operating Core: employees who create the product or service
2. Strategic Apex: general managers and personal staff
3. Middle Line: middle management

4. Technostructure: houses analysts who do the standardizing

5. Support Staff: employees who provide indirect support

<u>5 mechanisms of coordination:</u>

1. Direct Supervision: one person gives orders (for instance the manager)

2. Standardization of Work Processes: standards to guide work being done (for instance work orders)

3. Standardization of Outputs: performance measures to guide work being done

4. Standardization of Skills: employees are trained prior to beginning work (for instance: training)

5. Manual Adjustment: employees coordinate their own work (for instance: informal communication)

<u>5 structural configurations:</u>

1. Simple Structure: Not elaborate so the organization can change quickly (simple and dynamic)

2. Machine Bureaucracy: routine, formalized workflow (simple and stable) (for instance: Mass production firms)

3. Professional Bureaucracy: "standardized by a coordinating mechanism that allows for decentralization" (p. 333) (complex and stable) (for instance: School systems)

4. Divisionalized Form: "superimposition of one structure on others" (p. 335) (for instance: Central headquarters overseeing divisions)

5. Adhocracy: “little formalization of behavior” (p. 337) (complex and dynamic)

<u>5 types of decentralization: (design of the decision making system)</u>

1. Vertical and Horizontal Centralization: power is at the top (strategic apex)
2. Limited Horizontal Decentralization: power flows outside the authoritative line
3. Horizontal and Vertical Decentralization: power flows down the authoritative line then out at the bottom (operators)
4. Limited Vertical Decentralization: power is delegated down the authoritative line
5. Selective Vertical and Horizontal Decentralization: power is diffused throughout the organization

<u>5 contingency factors: (have an effect on structure)</u>

1. Age
2. Size
3. Technical System
4. Environment: dynamic, market influences, hostile
5. Power: focus of…

On page 330 Mintzberg presents a chart showing the interface of these sets of five. Both the simple and professional bureaucracy structures are exemplified in this journal summary. Simple structures tend to be coordinated through direct supervision and have a centralized decision making system. They usually are young, small, have little technical systems, dynamic environments, and the focus of power is with upper management. Professional bureaucracy structures are coordinated through a standardization of skills and have power diffused throughout the organization. They are young, vary in size, have low regulation but could have a high complexity of technical systems. Their environment is highly complex and dynamic with the focus of power on the experts.

Mintzberg and Waters (1985) place deliberate and emergent strategies along the two ends of a continuum. In between, they identify eight additional strategies (typology), each defined below.

1. Planned: 'surprise-free' (p. 259)
2. Entrepreneurial: One person (owner) imposes vision
3. Ideological: Collective strong identity with a vision (shared)
4. Umbrella: Leaders have partial control (cannot set vision deliberately but set boundaries)
5. Process: Leaders control the process of strategy making not the content
6. Unconnected: Strategies are emergent from the organization at large. They may or may not fall within an umbrella.
7. Consensus: Natural convergence of themes by a mutual adjustment among groups
8. Imposed: Strategy is forced from the outside (environmental influences Ex. client)

These eight strategy formations can be investigated based on the "function of the structure and context of organization" (p. 269). Furthermore, "will (strategies) tend to be more deliberate in tightly coupled, centrally controlled organizations and more emergent in decentralized, loosely coupled ones?" (p. 269). What about 'strategic learning'? How do managers learn from their experiences? How do they realize strategies? How do they track strategies? Emergent implies learning. Pattern recognition over time is a form of self-awareness that paves the way for future research and understanding of organizational strategies.

2.5 Teamwork in Organizations

Salas, Burke, and Cannon-Bowers (2000) assessed the nature of teamworking and reviewed the different efforts made in the management literature to define it. They found that decision-making is one of the core skills in teamworking. Another element that Delbridge, Lowe, and Oliver (2000) plus Glover (2002) concluded is that clearly defined team roles are important. This is the highest importance human relation skill, as described by Partington and Harris (1999). The authors researched the implementation of teamworking in the car industry. In addition to measuring the success of implementing teamwork in the industry, they found evidence for teamwork training. They emphasize that successful teamworking is not as easy as just putting people together and expecting them to function.

A popular perspective from Findlay, McKinlay, Marks, and Thompson (2000), is to look at a company or an industry at large and assess the impacts of teamworking on the environment as a whole. Bacon and Blyton (2000) looked at the iron and steel industry and investigated how teamworking had changed the way work was conducted. They concluded that workers' positive experience and company performance increase were dependent on management objectives for improving teamwork. Glassop (2002) researched the success of implementing teamworking in an Australian industry. She found that the introduction of teamwork in the workplace can be successful depending on the type of work. Not all jobs are compatible with teamwork. Indeed, as with any implementation of work and organization design, teamwork is more appropriate to some settings than others (Mueller, Procter, and Buchanan, 2000).

Other writers argue that "it is entirely possible to force a team-based form of work design onto a process with a non-compatible characteristic." However, work designs should reflect the features of the production process (Sprigg, Jackson, and Parker, 2000). They did similar research on employees in wire mills and looked at the success of teamwork implementation. Coradetti (1994) supports this group of researchers, claiming that teamworking is not a fast fix and organizations must give it a chance in relation to time and resources.

The success of teamworking in the workplace is also explored by Clark, Amundson, and Cardy (2002). They interviewed members of cross-functional teams in large multi-site companies. The purpose was to report on the progress of this new element (teamworking) within the work organization. These authors focused on learning outcomes for both the organization and the employees themselves.

Grint (1991) researched the positive impact of implementing better teamworking through nursing teams when communication became more effective. He concluded that teamwork could provide better primary care. In this connection, decision-making was one of the successes found when implementing teamwork. Howard (1997) also confirms the benefits of teamwork and the increased use of teamwork in the health service industry. He states that many hospitals are modifying their whole organizational structure to embrace teams.

De Jong, Bouhuys, and Barnhoorn (1999) conducted research on the effectiveness of management teams. The aim was to find a positive link between extraversion and conscientiousness to self-efficacy for participating in teams and the attraction to teamwork. Another perspective on team composition is taken by Chrispeels, Castillo, and Brown (2000). They looked at the makeup of school leadership teams. The team composition had different members of the groups: students, parents, and staff. The study also looked at the impact of team member training in-group processes. Hollenbeck, Ilgen, LePine, Colquitt, and Hedlund (1998) investigated the importance of feedback to a team for ensuring team performance. A similar study was conducted on a university hospital by Hyrkas, and Appelqvist-Schmidlechner (2003). They found that supervision improved the decision making in the teams.

Knights and McCabe (2000) wanted to explore the impact of teamwork for employees in the automobile industry. The authors argue that because there is no single form of teamworking, there is no single experience of what teamworking means to an employee. One interesting finding was that some employees, while being committed to teamworking, were actually aware that it required a psychological change. Leonard, Scholl, and Kowalski (1999) tried to find the correlation between the four most used schemes for measuring the cognitive styles of decision-making. They found that even though there was a lot of overlap, there were a few strong inter-relationships between themes.

2.5.1 Gender and Teamwork

Another perspective of research on teamwork is the element of gender difference in teams. LePine, Hollenbeck, Ilgen, Colquitt, and Aleksander Ellis (2002) looked at how the gender composition of a group influenced team decision-making. Performing traditionally masculine tasks, they found that the team decisions grew more and more aggressive as the percentage of male team members increased. Men and women have different problem solving preferences that will influence the team decision-making process (Glover, 2002). Sommerville and Dalziel (1998) explored the linkage between team role preferences and the kind of study selected by students to see if there is a difference between male and female students. They also assessed that the majority of males were implementers (25%) or coordinators (23%), whereas the majority of women were team workers (45%). Also, the majority of business and occupational therapy students were team workers (24% males and 50% females).

Chapter 3

RESEARCH METHODOLOGY

The research methodology developed for this dissertation is summarized in Figure 2 below. This chapter details the research method and presents the reasoning behind it.

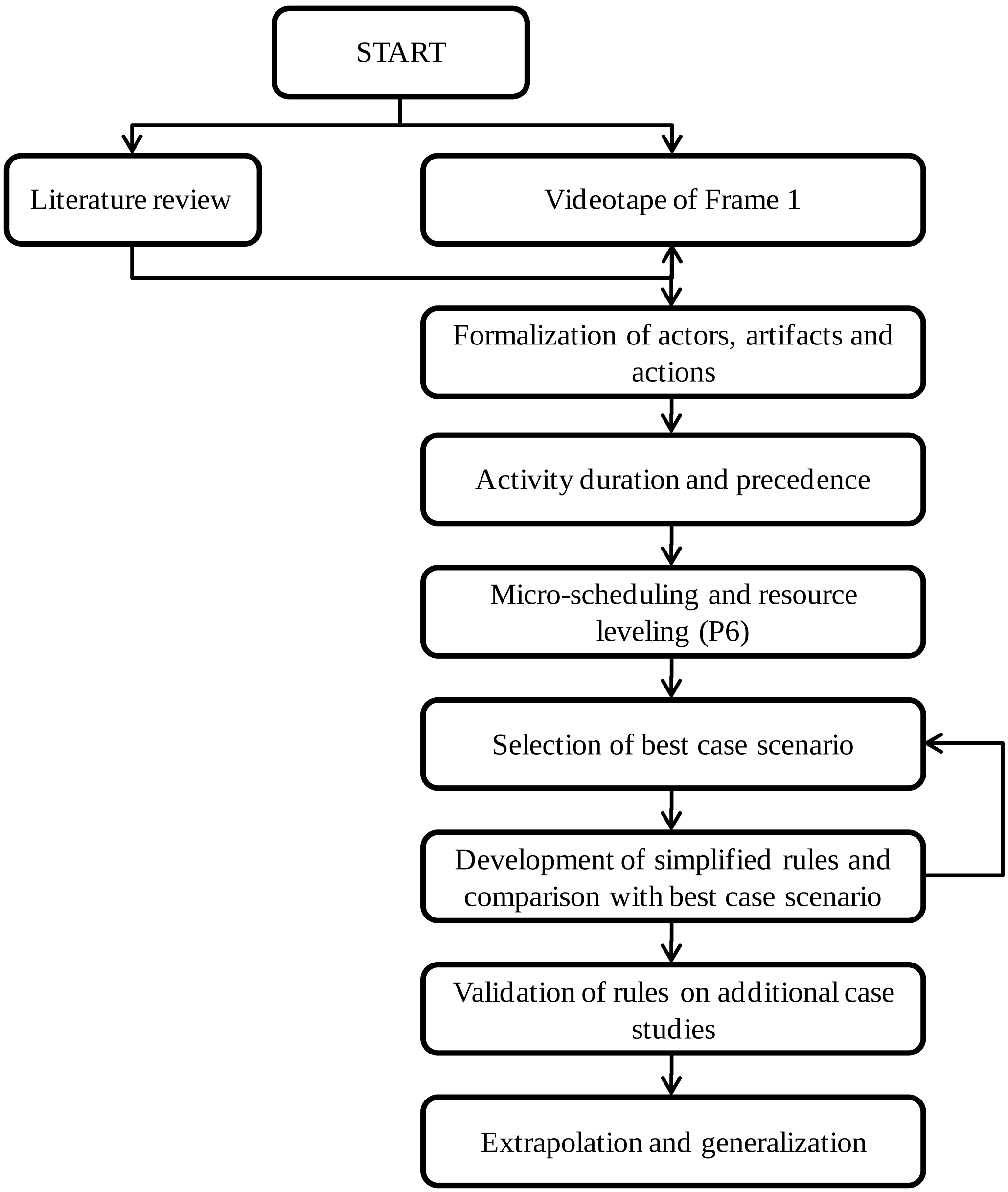

Figure 2. Methodology path for this research

3.1 Qualitative and Quantitative Research Data of This Study

As stated in section 1.5, the assumptions made at the beginning of this research are that the members of the effective teams share a mental model of the final product (how the frame will look) and a silent understanding of the sequence of tasks to be performed by each team member. To confirm these assumption, the researcher started by examining videotaped activities of two or more framers constructing residential interior and exterior walls. The walls were either bearing or non-bearing to the general structure to be built. The observation of the actors (framers), artifacts (studs, plates, nails, etc.), actions, and movements were identified and recorded. The data obtained was implemented in a planning and scheduling software (P6) and further analyzed. The results were then compared to the initial observations. Differences observed were quantified and recorded, analyzed, thus creating a new understanding of the observed activities. This new understanding was captured in a set of rules that were further analyzed and their result compared to the best case scenario given by the scheduling software. The case study approach is the most appropriate because we have little formalized knowledge on how the work practices and team processes increase task performance and accident awareness. Field studies enable the investigation of the phenomenon in its real-life context. The use of multiple videotaped cases enables analysis and generalization through identification of more universal principles regarding how effective teams structure and coordinate their work. The comparison with other performing teams identifies differences and makes possible the validation of this research.

The case studies also allowed the extrapolation of the conclusions to a form that can be used to select the most appropriate person for a team. As a qualitative research methodology, the study is to be grounded in several bodies of knowledge from psychology to cognitive engineering and validated with empirical studies. The research is capturing and formalizing the elements of work design and production engaged practices. The performance of task collaboration is seen in this research as part of the work plan execution. A preliminary model (Figure 3) was adopted from Lehto (1993) to illustrate team interaction and their behaviors. According to Lehto, the levels of interactions considered as behaviors are judgment, knowledge, rule, and skill based. Connections between these levels appear to be fundamental to achieving effectiveness in teams. The relationships between levels refine the model and confirm accuracy of the team mental model. The team mental model is defined as the representation of the decision-making process in the mind of each team member.

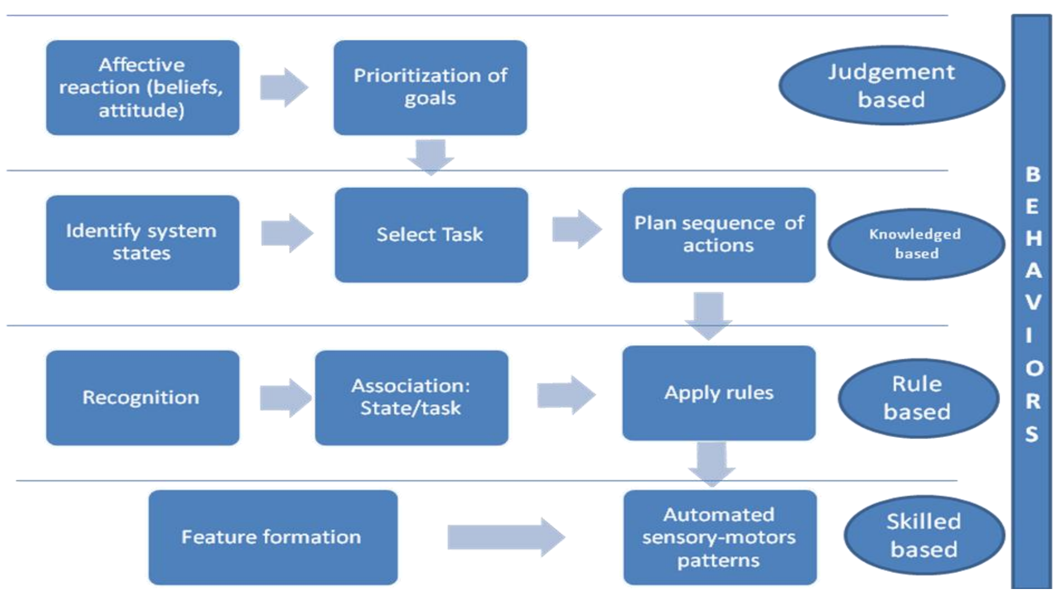

Figure 3. Mental model and levels of performance (adapted Lehto, 1993)

3.1.1 Use of Planning and Scheduling Software

To evaluate the performance of any given crew, actual measured times have to be compared with minimal possible achievable time. This minimal achievable time can be only obtained using optimized activity networks as implemented in planning and scheduling programs.

The use of planning and scheduling (P&S) software has been common practice in construction for about three decades (Liberatore, Johnson and Smith, 2001). As the use of P&S software has concentrated on solving problems at the whole project level, the level of detail about the activities is normally lower (i.e. more detailed) than the equivalent of level five in the Construction Specification Institute (CSI) Work Breakdown Structure (WBS) (CSI Master Format, 2010). From the point of view of task distribution and execution at the crew level, CSI level five is a "macro" level. The detailed application of P&S principles in a project is called micro-scheduling in this paper.

Whereas crew sizes and task sequencing are usually done at the foreman's level, P&S principles can be used to determine the most effective size of a crew and the best way of distributing the work among crew members. However, the purpose of the research presented here is to develop communicable collaboration principles that can be implemented by any crew rather than to have the construction crews distribute the work by running P&S software. P&S software was used only to find the optimal size of the crew, minimal time and to serve as a comparison with the performance of the well-organized crews. Well-organized crews probably use the same collaboration principles intuitively, but it was too difficult to capture those principles (Mitropoulos and Cupido, 2009). The study presented here applies to framers involved in the production of interior wall wood frames in residential and non-residential buildings.

Research in P&S has focused on optimization at the higher (activity) level of operations. Newer algorithms, such as The Sequence Step Algorithm (Srisuwanrat, 2009), deal with minimizing the duration of repetitive projects with probabilistic activity durations, while achieving continuous resource utilization. This has applicability at the activity level in the macro-scheduling of construction projects. Other authors (Kastor and Sirakoulis, 2009) were concerned with PERT/CPM (Programme Evaluation Review Technique/Critical Path Method) network techniques that are based on the assumption that all needed resources will be available. The scarcity of resources is usually a reason for project delays. Project Management software packages were studied to see how resource conflicts are resolved by using resource leveling. Their work evaluates the effectiveness of resource leveling tools of three popular packages by comparing the results when leveling two real construction projects as case studies. There are also misconceptions identified by other researchers about project scheduling and time management related to resource constraints (Herroelen and Leus, 2005). The misconceptions relate to the role of the critical path, the critical sequence (critical chain), active schedules, and the insertion of buffers in the baseline schedule as a protective mechanism against schedule distortions during project execution. The possible errors revealed by their research are illustrated using example schedules developed for an illustrative project.

Shortcomings in existing methods, for the identification of critical tasks in resource-constrained projects in situations involving more than one unit of renewable resource are highlighted through examples of research done by Rivera and Duran (2004). The concepts of critical set and critical cloud are proposed in their paper as an extension to the concept of critical task. The researchers allow a consistent and unified treatment of criticality in projects with resource constraints, and provide an unambiguous procedure to establish the critical sequence and its constituents. An algorithm to determine “critical sets” and “critical clouds” is proposed and applied to a sample project.

Although these algorithms are useful for optimizing whole projects, field personnel and crafts people need simpler principles to optimize the productivity of their crews. The study presented in this paper uses resource constraining algorithms and priorities from P & S programs to determine if simpler task priority principles (i.e. what should be done next if there is an available choice of tasks) can be derived from those algorithms. The research considers the limitation of resources (number of framers) and the pool of available tasks required to be accomplished for completing wood frames for interior and exterior walls. The process of assigning tasks to the resources (framers), their descriptions, and codifying of the tasks is shown in the next section. To put it simply, the problem statement can be reduced to the following question: how does one decide who does what and when, in an effective crew?

This study also has focused on the suitability of commercial project management programs like Primavera (P6) for micro-scheduling the framers’ tasks when building wall frames, as well as the effectiveness of these software packages to enhance the optimum team composition and task allotment (i.e. who does what and when). Specifically at this stage, in the methodology the following two goals were sought:

1. Test the influence of various resource leveling principles on the total productivity of the framing crew.
2. Test the feasibility of task automation sequencing and determine the needs to transfer this information into a “mental model” easily understood by the framers.

3.2 Data Collection and Analysis

The building of a wood frame structure was videotaped and analyzed frame-by-frame. The structure was built by two framers. The specific tasks performed (such as handling, marking, and cutting) and the duration of each task (in seconds) was recorded. The tasks were then generalized to allow application of general principles to instances of specific elements or assemblies. For instance, the task “cutting” can be applied to any of the studs in the frame. Cutting is preceded either by both measuring and marking or by aligning with another element.

However, task precedence is only one of the three types of constraints taken into account. The constraints to the tasks are: 1) Precedence constraints; 2) Resource availability constraints for specific tasks; 3) Resource continuity constraints for specific tasks. Although precedence constraints specify the technological order of work, resource availability and continuity constraints control the utilization of resources in the framing activity. To obtain a practical and efficient schedule, the three types of constraints presented above must be accounted for in micro-project scheduling.

In practice, a precedent network was created for all of the framers' tasks. Because the support of the P&S programs is geared towards macro-scheduling, the time was altered by considering each second as one day in the schedule. Each individual task was then assigned the resource of one framer and the duration was measured from the recording. The precedence network was then run on the P&S program, with each of the available resource leveling options. This battery of calculations was performed with increasing resource limits until the total duration of the activity (building the frame) stabilized at an absolute minimum value (i.e. adding more framers would not reduce the total time of building the frame). The results were recorded and analyzed.

The types of times framers are executing are categorized as follows:

- Productive time (physical work that contributes to the execution of tasks)
- Non-productive time (fixing errors, moving around for tools or studs)
- Counter-productive time (making the actual errors)

In the assigning of time to all framers, in all frames, the following times were not accounted:

- Cleaning
- Walking (traveling between task executions)
- Manipulation of tools (outside of close vicinity)
- Staying idle (looking around, sitting, etc.)

3.3 Developing a Notation Method for Elements and Tasks

The wood frame shown in Figure 4 was built by two framers (case study one). Figure 4 shows the as-built of the frame with all the elements in place, including nails.

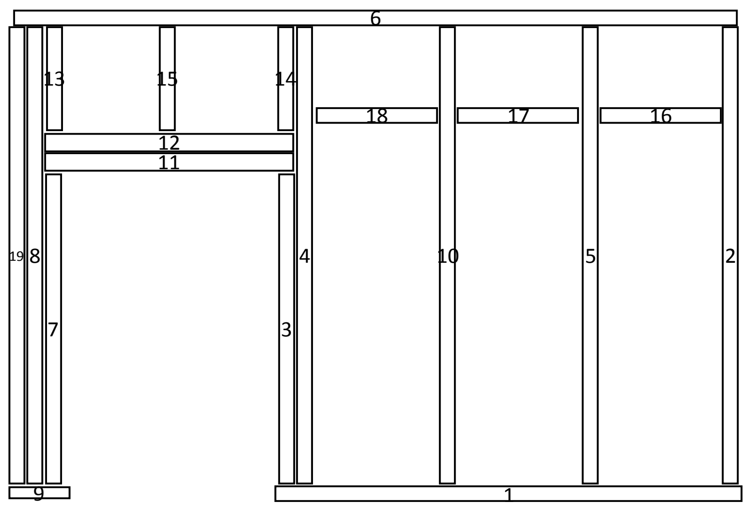

Figure 4. Interior wall – a wood frame built on-site by framers

A generic notation was developed for the implementation of the tasks for micro-level scheduling. Each element was identified by a two-digit code (01, 02…. 19) and each nail was identified by the code of the element it connects. Seven types of tasks were identified, as described below. The names were selected so they can be identified by their initial only.

- Handle (element XX or stud XX).
- Tape measure (element XX or stud XX).
- In-field measure (or In-situ measure of element XX).
- Mark XX_YY(ZZ) (mark element YY or ZZ on element XX).
- Cut (element XX or stud XX).

- Place (element XX or stud XX).
- Nail (side and toe nailing) XX_YY (nail element XX to element YY – the head of the nail is in element XX).

Therefore, all actions assigned to the available studs represent all tasks available for execution. For example, the available tasks pertaining to element 6 for one labor resource are as follows: H 06, T 06, C 06, P 06, M 06 05, M 06 10, M 06 13, M 06 14, M 06 15, M 06 34, M 06 78, N 06 02, N 06 34, N 06 05, N 06 78, N 06 10, N 06 14, N 06 15 and N 06 19. Note that elements 3 and 4, as well as 7 and 8 form two sub-assemblies; therefore, they are considered in the related tasks together after nailing them as pairs. These tasks were entered in Primavera P6 software for the purpose of scheduling and resource leveling. The duration of each task was recorded and introduced in both programs. A total of 120 tasks were identified, including both the tasks of starting and finishing the frame (lifting and placing in a determined location). Except for lifting, each task (such as C 06) requires that one resource (one framer) and only one be assigned to it.

3.3.1 Assignment of Actions and Primavera P6 Implementation – Determination of Tasks (from Elements to Tasks)

The duration of each task, such as lumber handling, measuring and marking, cutting, placing, and nailing was measured directly from the video-taped activity for each instance. In other words, if C 15 took 3 seconds and C 18 took 2 seconds, each was introduced with their own duration.

Task precedence was determined using elementary geometrical and logical reasoning. Specifically, the rules used consisted of the following precedence chain for any element: Handle, Measure and Mark, Cut, Nail, or Place. Note that Nail and Place are both successors of Cut. There are some situations when two elements are nailed together even if they are not yet in their final place. An example is E 03 and E 04 that are nailed together to form element 34. The possibility of generating other subassemblies (i.e. other than E 34 and E 78) is not considered in this study but it is mentioned later. The study focused on improving the efficiency of the current construction method only.

Practically (emphasized later in the validation chapter) all studs follow the general sequence of H→T→M→C→P. The exception is made by precut elements that do not have to be measured and cut; these studs were usually cut near the location of the jobsite and transported by one of the framers within the crew or by a helper (usually a novice framer) outside of the crew.

Furthermore, any nail that is covered by an element (such as N 11 03 covered by 12), will precede the placement of the covering element. For example, in the notation introduced here: N 11 03 → P 12. Using these rules, the precedence table can be created semi-automatically. An excerpt of the precedence table is reproduced in Table 5. For a full list of the precedence table see Appendix D, table D1.

Table 5. Predecessors for Elements 11 and 12, Frame 1

Element	TASKS	Predecessors
E 11	H 11	S
	T 11	H 11
	C 11	T 11
	M 04 11	H 04
	M 08 11	H 08
	P 11	C 11, M 04 11, M 08 11
E 12	H 12	S
	T 12	H 12
	C 12	T 12
	P 12	C 12, P 11, N 11 34

Note that the placing of element 11 and element 12 (i.e. P 11 and P 12) have respectively different types of precedent tasks. As stated before, these precedents have been determined from geometric and technological conditions. Special rules were considered and were incorporated for the two existing subassemblies, specifically pertaining to elements 3, 4 and 7, 8 (shown in Table 6):

Table 6. Predecessors Rules for Element 3-4 and 7-8, Frame 1

Element	TASKS	Predecessors Rules
E 34	M 01 34	H 01
	M 06 34	H 06
	P 34	N 03 04, M 01 34, M 06 34
E 78	M 09 78	H 09
	M 06 78	H 06
	P 78	N 07 08, M 09 78, M 06 78

3.3.2 Constraints and Priority Rules Optimization

When constraining and leveling resources, Primavera P6 uses priority, rule-based algorithms to generate workable schedules. The priorities come into play when two or more activities/tasks compete for the same resource, at the same time. P6 allows the user to select the preferred priority from a list of predetermined options. Some of these priority options are Activity ID, Activity Priority, Early Finish (EF), Early Start (ES), Free Float (FF), Late Finish (LF), Late Start (LS), Total Float (TF), etc. There are other classified priority rules such as Original Duration, by Department, by Phase, by Planned Finished or Planned Start, remaining Duration, and by Responsibility. These additional priorities were deemed irrelevant for the purpose of micro-scheduling and thus not taken into account when priorities were run for results. The reason for ignoring these options was to not alter the final results when strictly applying priority rules or leveling orders. However, it is recommended that future research investigates these leveling possibilities applied individually to priority rules or leveling orders.

3.3.2.1 Special Case-Subassemblies

As mentioned before, the possibility of generating other subassemblies (i.e. of Frame 1, other than E 34 and E 78) was not considered in this study. This is because the study is focusing on improving the efficiency of the current construction method only. However, there are cases in which (as described in the later chapters for other frames) the subassemblies are playing an important role in the division of the work between the framers or they require a considerable amount of total tasks for one framer to execute. These cases are treated in a separate manner, but are sufficiently described in the data analysis and the other analyzed case studies.

Table 7: Subassemblies in the First Frame - Case Study 1

Case study/Frame	1/ Frame one
Subassemblies	E 3 + E 4= E 34 E 7 + E 8= E 78
Total	**2**

As seen in Table 7 above, a total of 2 subassemblies were identified in the Frame 1- case study one respectively.

All other frames are presented as additional case studies in the next chapter, with the respective subassemblies considered in the process of on-site construction.

The data analysis and development of the set of rules is presented in Chapter 5.

Chapter 4

CASE STUDIES OF FRAMING PROCESSES

4.1 Description of Frames and their Complexity

In the following sections, the four frames with their exact composition (studs composition) are illustrated and described. The case studies were selected randomly as videotaped on the job-site, even though an increase complexity is perceived in each case. Studs used are lumber, usually 2x4s, but 2x6s are used when 6-inch insulation is desired in the exterior walls. Studs are spaced 16" on-center in all case studies, but the measure is dependent on the geometrical arrangement of that particular wall (interior or exterior).

Top and bottom members of the walls are "top" and "sole" plates and they usually consist of doubled 2-inch stock. Headers or lintels are running usually at right angles to the studs. They form the top of the window, door and other wall openings, such as fireplaces. Headers must be strong enough to support the load above the opening. The depth of the header depends on the width of the opening. As the width of the opening increases, so must the strength of the header. There are a multitude of headers; some of them have spacers sandwiched in between. Glulam beams are often used for headers and sometimes parallel strand lumber makes excellent headers for doors and windows.

Jack-studs or trimmers are shortened studs that line the sides of an opening. They extend from the bottom plate up to the top of the opening. Cripple studs are shorter members above and below an opening, which can extend from the top or the bottom plates to the opening.

All the studs were assigned unique numbers to delineate them in the frame structure. Usually the notation came to each stud from the witnessed sequence of attachment in the frame based on the video observation. The numerical value has also the role of assigning all the related tasks performed to them based on the witnessed actions, until the final position is tightened in the frame for each individual stud.

4.2 Case Study One – Frame 1

Frame one is described in Figure 3, chapter 3, and it provides a basis for the methodology. It is an interior wall that has a singular opening (a door) and the header for the door consists of two trimmed regular studs, one on the top of the other (quite unusual, as declared by interviewed experts). In this particular frame, there are a total of 19 studs, 3 cripple studs and 3 fire-blocks. This frame is an actual interior-partitioning wall for a residential first floor structure. Initially, element 9 was wrongly attached to the structure (i.e. the cutting of element 9 the second time was added to the time of the N 09 78 task). This performed nailing came out longer because of the reattachment of stud 9 to assembly 78 after being re-cut (shortened).

4.3 Case Study Two – Frame 2

As stated previously, the frames in discussion consist of plates (sole and top plate), studs (king, jack and cripple studs) and headers (above door and/or window opening) with or without a sill. Frame two is an interior wall while frames three and four are exterior walls. The following frames were erected by two framers with or without a helper and were named after the color of their protective hat (for video identification purposes).

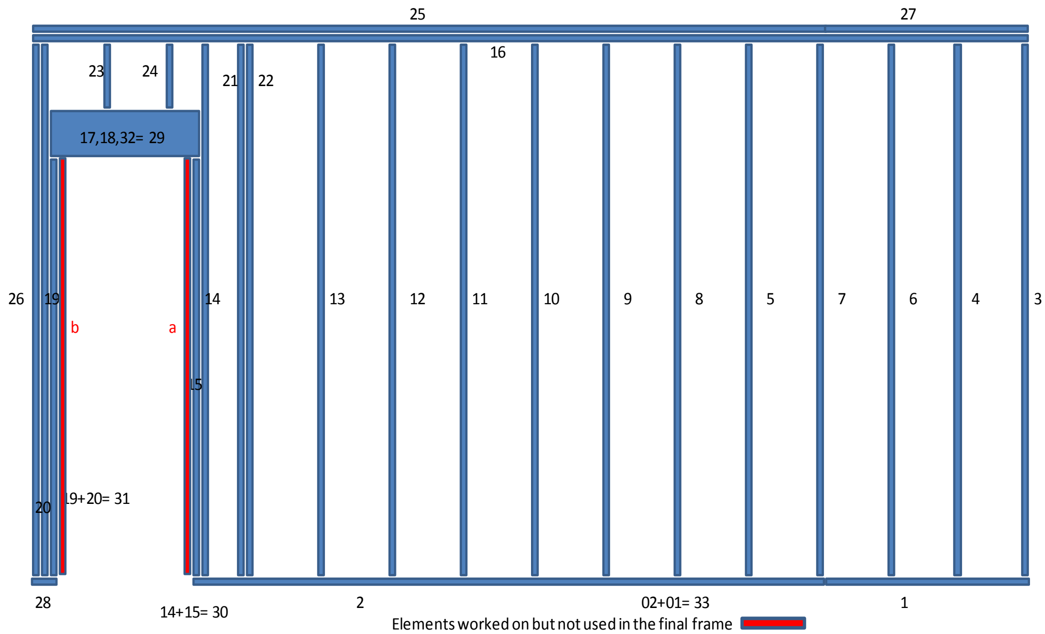

Figure 5: Frame two - interior wall with one door

For this frame, a numeric value was assigned to each element (01, 02…28) based on the sequence of their erection. A total of 28 elements were identified in frame two. All the elements in discussion were then assigned most of the seven different actions - Handle, Tape/In-situ measure, Measure and Mark, Cut, Place and Nail. For instance, all the tasks associated with Element 23 in Frame one are as follows: H 23, T 23, C 23, M 23 16, P 23, N 16 23 and N 23 29.

4.4 Case Study Three – Frame 3

Frame three identified a total of 37 elements. (Figure 6)

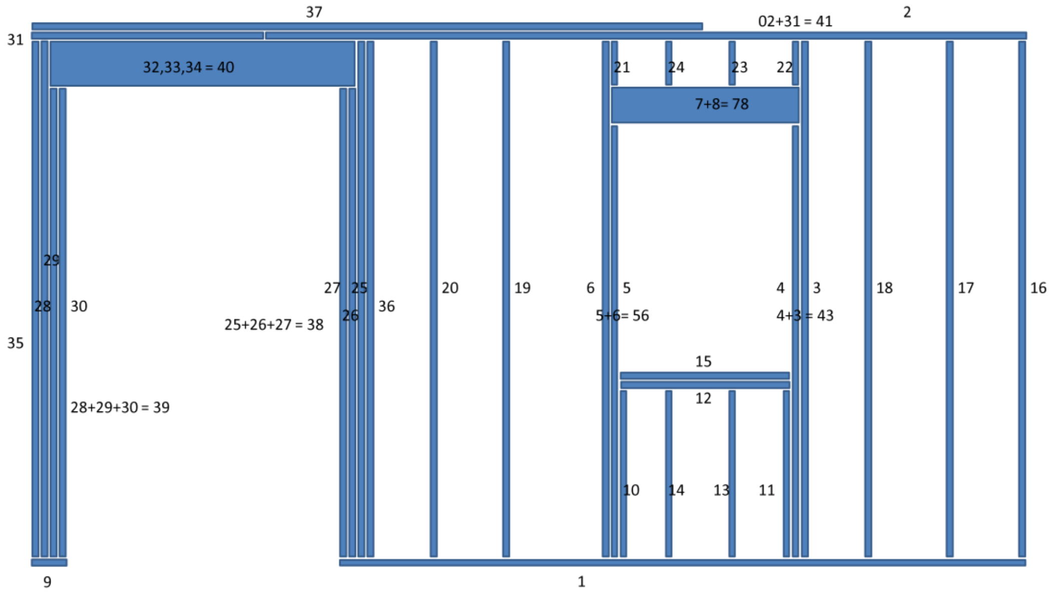

Figure 6: Frame three - exterior wall with one door and one window opening

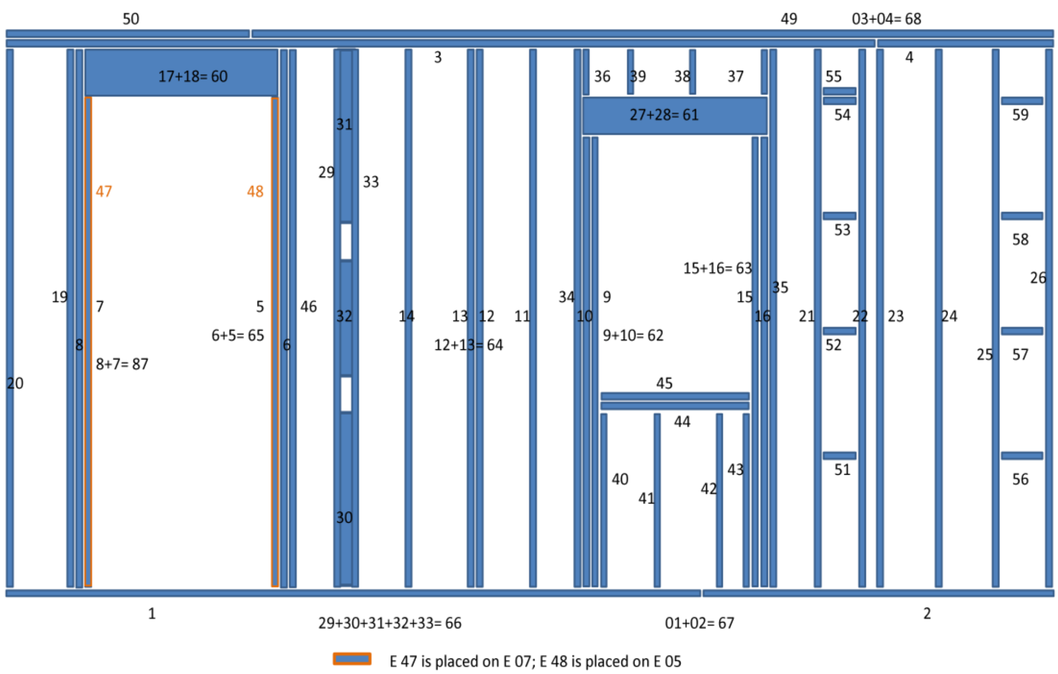

Figure 7: Frame four - exterior wall with one door and one window opening

4.5 Case Study Four – Frame 4

Frame four is identifiable through a total of 59 elements and presents an increased complexity (Figure 7). Certain Elements (e.g. E 18 in Frame four) do not have task handle (H). This is because E 17 and E 18 are marked on a single piece of lumber and then cut to form E 17 and E 18. The time for handling this lumber is allocated to E 17 (H 17) for convenience and E 18 does not have Handling (H 18). Task precedence was determined using elementary geometrical and logical reasoning (Maghiar et. al., 2010). For every element, the precedence chain was Handle, Measure and Mark, Cut, Place, or Nail. In situations in which two elements are cut from the single lumber, the predecessors are as in Table 8. Note E 41 does not have H 41 hence the predecessor for T 41 is H 40.

Table 8: Frame Four: Predecessors for E 40 and 41

Element	Task	Predecessor
E 40	H 40	S
	T 40	H 40
	C 40	T 40
	P 40	C 40
E 41	T 41	H 40
	C 41	T 41
	M 01 41	H 01
	M 44 41	H 44
	P 41	M 44 41, M 01 41, C 41

Also, any nail that is covered by an element (just as N 16 05 covered by E 25), will precede the placement of the covering element as shown in Table 9.

Table 9: Frame Two: Predecessor for E 25

Element	Task	Predecessor
E 25	H 25	S
	T 25	H 25
	C 25	T 25
	P 25	C 25, N 16 07, N 16 05, N 16 08, N 16 09, N 16 10, N 16 11, N 16 12, N 16 13, N 16 21, N 16 22, N 16 30, N 16 24, N 16 23, N 16 31

<u>Task Duration</u>:

Each task is assigned a fixed duration derived from the video-tape. For instance, in Frame two, H 16 took 13seconds(s); P 16 took 5s and each was assigned those respective durations. Some tasks were repeated due to errors and the duration for those was added to their initially assigned duration. An example from Frame two is task M 02 10 = 10s (2s + 8s). Here marking E10 on E02 took 2s. However, the step was repeated due to alignment error requiring an additional 8s to fix the problem; the total duration summing up to 10s. Two additional tasks "a and b" (shown in Figure 5) were identified as error elements that were a part of the process, but did not add to the final frame. However their duration was considered and added to the prior task to account for the labor and time spent on those elements. In other words, the time in seconds associated with element a – H 0a, T 0a, C 0a and N 0a 15 14 were added to H 15, T 15, C 15 and N 14 15 respectively.

This type of duration assignment was deemed necessary to be able to calculate the influence of activity sequencing on the crew productivity. In other words, the "optimal duration" was calculated for the "as built" frame rather than the "as designed" frame. This approach allows separating the error made in the performance of a unique and singular task from the influence of the decision about the task sequencing. In terms of the assumption made at the beginning of this research, this approach separates the "what needs to be built" from the "how to build it".

Subassemblies:

As seen in Table 10, a total of 4, 7 and 9 subassemblies were identified in each of the three Frames respectively. In Frame two, Elements 14 and 15, 19 and 20 and 17, 18 and 32 form subassemblies 30, 31 and 29 respectively. They are recognized as subassemblies because they are nailed to form pairs even prior to placing them in position, for example, H 19, T 19, C 19, H 20, N 19 20, P 31, N 16 31, N 26 31, N 28 31. Once E 19 is nailed to E 20 (N 19 20) they form the subassembly named E 31. In subassembly E 29, E 32 is a particle board sandwiched between E 17 and E 18. It should be noted that different materials require different measure and mark techniques (thread versus measuring tape). However, material difference (lumber vs. particle board) is not considered part of this study.

Table 10: Subassemblies in the Last Three Frames

Case study/Frame	2 / Frame two	3 / Frame three	4 / Frame four
Subassemblies	E 17+18+32= 29 E 14+15= 30 E 19+20= 31 E 02+01= 33	E 25+26+27= 38 E 28+29+30= 39 E 32+33+34= 40 E 05+06= 56 E 04+03= 43 E 07+08= 78 E 02+31= 41	E 17+18= 60 E 27+28= 61 E 09+10= 62 E 15+16= 63 E12+E13= 64 E 06+05= 65 E 29+30+31+32+33= 66 E 01+ 02 = 67 E 03+04 = 68
Total	**4**	**7**	**9**

As mentioned in the methodology, task precedence was determined using elementary geometrical and logical reasoning. For example, in Frame two precedence for P 25 are C 25, N 16 07, N 16 05, N 16 08, N 16 09, N 16 10, N 16 11, N 16 12, N 16 13, N 16 21, N 16 22, N 16 30, N 16 24, N 16 23 and N 16 31. Here E 25 cannot be placed in its final position unless it is cut to the desired length. Also, P 25 covers certain nails (e.g. N 16 12) and requires that this nailing operation precede P 25. Also, for **M** XX_YY the predecessor is **H** XX or **P** XX (**P**lace if XX is a sub-assembly without a task **H** XX). E.g. in Frame four, for M 63 44 the predecessor is P 63; for M 62 44 the predecessor is H 62 where both 62 and 63 are sub-assemblies.

To complete the loop, the successor for all Nailing tasks (N 01 03, N 01 04……) was Lift. However, some subassemblies such as N 17 18 32 and N 15 14 (Frame two) have H 29 and H 30 as their respective successors while N 29 30 has P 31 as the successor depending on how they were handled. Each task was then assigned resources as observed in the videotape. The task sequence was adjusted to eliminate existing idle times to the best possible extent.

Chapter 5

DATA ANALYSIS

5.1 Videotaping of Framing Crews

Video recordings were used for detailed observations because in terms of data capture it has the most obvious advantages: the audio and the dynamic images can at any time supplement the researcher notes and verbal or written observations. It also captures the nonverbal communication between the framers which proved to be essential later in the case studies. Nonverbal communication and individual awareness of others' work is not captured in any other forms of note-taking and direct observations. The analysis of the video frames is tedious and time-consuming, but it is always possible to revisit the frames and get the most accurate description of one's work through detailed tasks, without having the fear that something was skipped. Therefore, the researcher is not aware of any limitations to this methodology, but it did raise issues like confidentiality, which were overcome through direct approval from foremen and superintendents of the participating companies. There was also a "waited around" long enough timeframe for the crews to become accustomed to the video camera. Therefore, cameras being there for a sufficient amount of time, the framers resumed the "normal activity."

Further data were gathered from repetitive videos of the same process (wood framing- interior walls) and a critical path of the activities was obtained and carefully analyzed. A couple of superintendent experts were assigned to analyze the videos. Their opinions for specific procedures, methods, techniques, and tasks sequences were documented. Productive time, non-productive time and errors during the work process were analyzed relative to the overall activity. Idle time was carefully assessed to see if there is a connection with the decision-making process of team participants. Individual tasks and tandem tasks were considered for analysis. Therefore, the mental model revealed from the video analysis was superimposed with two quality issues:

1. How good is the model in reflecting the exact product formation in the minds of the participants
2. How well do the participants understand the model (reflected through the decisions to engage in the next available tasks and awareness of what others are doing)

To assess the two quality issues above, the duration of the actual activity was compared with the time that would have been obtained when all the team members have followed the best mental model at every step.

Therefore, all networks are analyzed as Ideal (Computer Optimized), Team (Rule-based Optimization) and Executed (Real-Life) plans. The computer optimized networks were further varied by changing the total number of available framers to study the influence of the crew size on productivity.

5.2 Cognitive Processes of the Construction Wood-Framing Work

Investigating more about the Cognitive Task Analysis (CTA) methods and having *a practitioner's guide to cognitive task analysis* as a main resource (Crandall, Klein and Hoffman, 2006), implementation in the study for so called Team CTA Technique was considered the best option. The incorporation of the study as one of the CTA analysis methods in the context of wood-framing environment was possible mainly due to videotaping the activity and performing video-analysis pertaining to cognitive processes.

According to Team CTA Technique, cognitive processes that are relevant from the video-analysis of framing teams include:

- control of attention (how teams engage in information management),
- shared situation awareness (how members have the same interpretation of ongoing events)
- shared mental models (how members have the same understanding of the dynamics of key processes and how well they are able to follow the rules of work)
- applications of strategies and heuristics to make decisions, solve problems (errors, conflict in work) and plan
- implementation of metacognition (how the team is able to monitor itself and determine when it is running into difficulties)

Based on these and other considerations, a couple of measures were developed. One measured individuals in each team from the construction productivity perspective, the other measured the team as a whole in each case study in order to establish later how individuals fit in the team (from cognitive engineering perspective). These measures are detailed more in the validation of results chapter of this document. To describe the video analysis pertaining to the methodology of the research, I use this opportunity to expand it further.

As delineated in the previous chapter, the building of wood frame structures was videotaped and analyzed in detail. The structures were built usually by two framers or by two framers helped by a novice framer. The specific tasks performed (such as handling, marking, and cutting) and the duration of each task (in seconds) were recorded. The tasks were then generalized to allow application of the general principles to instances of specific elements or assemblies. For instance, the task “cutting” can be applied to any of the studs in the frame. Cutting is preceded by both measuring and marking or by aligning (with another element). All these tasks were implemented in the Planning and Scheduling software for further analysis.

The following two types of constraints were imposed on each task to obtain a practical and efficient schedule:

- Predecessors: Task precedence was determined using elementary geometrical and logical reasoning.
- Resource allocation: Based on the observation from the videos, framers were assigned to each task. In case of an error, the framer who made the final rectification was assigned the task.

5.3 Minimum Possible Duration Using P6 and Resource Leveling

Using Primavera Project Management (P6), the total production time was computed for a matrix of scenarios. The matrix of scenarios contains the maximum number of available framers (resource limitation – starting from one and going up to fifteen framers for this software) and each of the resource leveling principles deemed applicable, as mentioned in the previous section. Table 11 presents the results of one resource-leveling principle (the most efficient one - Late Start), in P6 program. The productivity of the framers in a crew was calculated as the fraction of the standard time obtained with only one framer available. For instance, referring to Table 11, the productivity of the 3 framers crew was calculated as follows: Total duration of building the frame was 136s. Total labor-seconds for the 3 framers were 136s x 3 = 408s. The total labor seconds when resources were fully employed (i.e. one framer) was 384s. The difference, 408s – 384s = 24s, is deemed to be idle time distributed among the crew members. Productivity of the crew was calculated as 1 – 24s / 384s = 94%. It is worth noting that when using the resource leveling principle presented in Table 11, the total time stabilizes at 76s with a crew of 6 framers. Increasing the crew size above this limit will only reduce the productivity, but will not decrease the total production time. The CPM column shows the critical path obtained from running the respective resources through P6. In the case of the 3 framers, the critical path obtained after leveling pertained to tasks of element 6 and assembly 78. The duration column shows the percentage of the duration obtained after resource leveling relative to the absolute total duration when one resource (one framer) is used (384 s). Whereas the calculations do not take into account the synergies of the crew, they provide a consistent base for comparing the resource-leveling principles with one another. The points of interest are discussed below.

Table 11. Duration and Productivity in P6

Nr	Priority rule	Total duration	Resources units	Nr. People	CPM	Equiv. Time	Prod. Frame	Duration
1	**LS-Late Start**	384	100%	1	E19	384	100%	100%
		198	200%	2	E19	396	97%	52%
		136	300%	3	E6+E78	408	94%	35%
		104	400%	4	E6+E78	416	92%	27%
		86	500%	5	E6+E78	430	89%	22%
		76	600%	6	E6+E78	456	84%	20%
		76	700%	7	E6+E78	532	72%	20%
		76	800%	8	E6+E78	608	63%	20%
		76	900%	9	E6+E78	684	56%	20%
		76	1000%	10	E6+E78	760	51%	20%
		76	1100%	11	E6+E78	836	46%	20%
		76	1200%	12	E6+E78	912	42%	20%

The results of the calculations are incorporated in Figure 8. This figure superimposes all the leveling principle results ran on the software, increasing resources one-by-one. It is evident that the greatest benefit is obtained when moving from a one to two framer crew. A crew of three framers still has some benefits (i.e. project crushing). Increasing the crew to more than three framers offers no significant benefits. This conclusion, specific to the frame presented in Figure 4, was consistent for all leveling principles, in P6. As mentioned above, there were eight different priority rules applied to resource-leveling in P6. The results for the productivity and total duration are presented in Figures 8 and 9, respectively. These results show that the productivity of two to three person crews (i.e. total duration of the framing) depends significantly upon the resource-leveling principle. The other productivity and duration comparison charts (for different leveling priority rules in P6) of all other three case studies presented in the previous chapter are provided in Appendix B.

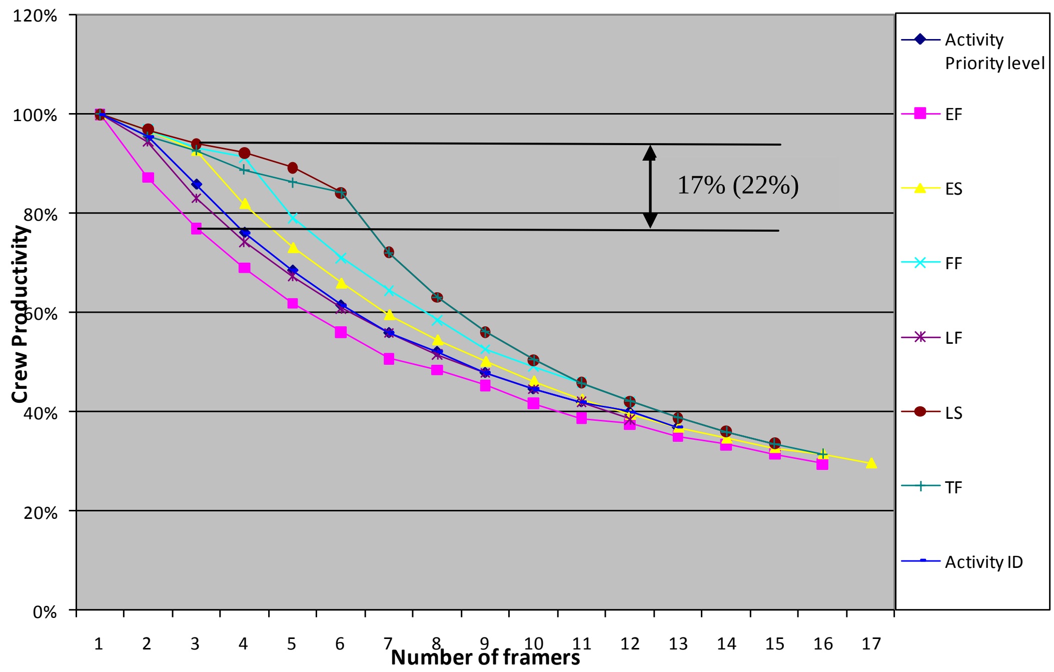

Figure 8. Productivity comparison for different leveling priority rules in P6

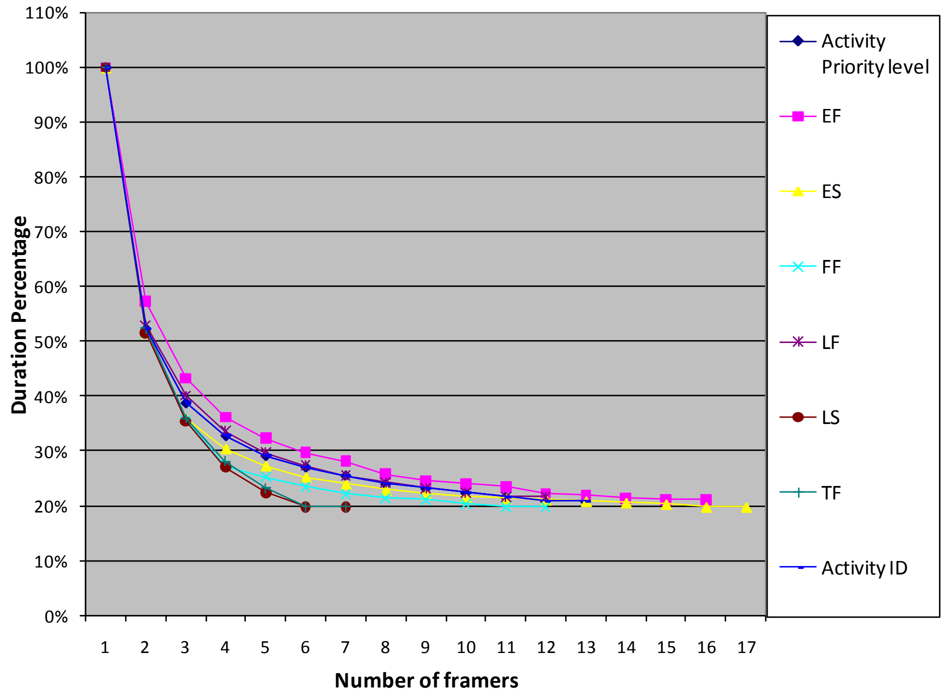

Figure 9. Duration comparison for different leveling priority rules in P6

For instance, looking at the case of three framers on the graph in Figure 8, one can notice that productivity varies between 77% when the EF priority rule was applied and 94% when the LS priority rule was applied. This means that, when faced with several choices of the next possible task, the framers' decision will influence the total productivity of the crew. A wrong decision will generate idle time downstream in the process. In the case above, the productivity improvement from EF priority to LS priority is 22% (17% increase related to the base of 77% is 22%).

As stated previously, the goals of this part of the study were:

1. Test the influence of various resource leveling principles on the total productivity of the framing crew
2. Test the feasibility of automation of task sequencing and determine the needs for the framer and his foreman to easily organize the work to make a more productive and safe environment for the crew

This section presents the conclusions and discussion for each goal:

1. Resource leveling principles play a significant role on crew productivity. For a team of three framers, the Late Start leveling priority resulted in a 22% productivity increase compared to Early Finish leveling priority for the first frame analyzed. This means that, when presented with a choice of tasks, the framers should choose the one with the earliest late start. However, because the principle of the earliest late start is only applicable to computer programs, an easier to explain method had to be developed. The next chapter presents an easily understood small set of rules that makes the whole crew more efficient. The application of these rules was represented through a flowchart.
2. The application of the micro-scheduling of tasks to various trades is universal. However, there are two conditions that must be satisfied when using the scheduling software. These two conditions refer to a clear description of the work (good definition of the tasks) and a geometrical reasoning, along with a technological reasoning assigned for relationships between tasks. Each of these topics requires further research. Identifying the task before the activity is performed requires a definition of task

taxonomies for various construction methods. A detailed task taxonomy based on a specific construction trade would be a first step in this direction. And the methodology of the study is implementable at a larger scale not just relative to construction trades. The optimization of the wood-framing tasks can be applied to any activities that can be described through a fair taxonomic work breakdown.

5.3.1 Extreme Cases

The following is the detail of the framers' activities in the two extreme cases, frame one.

Case 1: EARLY FINISH rule

Framer 1 can execute the following first eight tasks: H 05→H 12→H17→H 04→H 13→T 09→H 01→T 15

Framer 2 can execute the following first eight tasks: H 09→H 03→H15→H 02→H 11→T 03→T 13→M 05 16

Framer 3 can execute the following first eight tasks: H 14→H 05→H16→T 14→H 07→T 03→T 09→H 01

A more organized and logical sequence was obtained when the late start rule was applied for the activity (all tasks) in P6.

Case 2: LATE START rule

Framer 1 can execute the following first eight tasks: H 06→T 06→C 06→P 09→H 04→H 03→T 03→C 03

Framer 2 can execute the following first eight tasks: H 07→T 07→C 07→P 07→P 08→N 07 08→H 01→H 03

Framer 3 can execute the following first eight tasks: H 08→H 09→T 09→C 09→M 09 78→M 06 78→P 78→N 09 78

In this case, one can notice that P 09 is executed by framer 1, while the other tasks related to the element 9 are performed by framer 3 which implies frequent coordination issues (framer 3 was start working on handling the element 8). Even the more ”logical” sequence would be impossible to explain and implement in day-to-day operations. Hence, the research focused on developing and testing a simplified set of rules that is implementable yet gives total times that are comparable (close to) the minimal possible achievable time.

5.4 Simplification of Results – Training of Wood Framers

For the framing activity presented, the tasks were completely identified and defined by watching the video-capture of the real activity. Most of the precedence rules were generated automatically, using elementary formulas in Excel. Corrections were made manually to accommodate for exceptions. This algorithm provided a good validation to the idea that full automation of micro-scheduling is possible and worth pursuing.

The whole methodology is raising in essence two questions:

- How good (fitted) the common team plan is for the optimum performance?
- How well does the team execute the common plan?

Partly, these questions are answered in these two chapters: data analysis and validation of results. These mental models for achieving high-efficiencies are based on the geometrical complexities of the on-site built wood-frames and their perception of the “look ahead” workable micro-schedule of their entire activity.

Figure 10 depicts the process of developing the rule-set that may be used to train framers for increased crew productivity. A detailed description of a general flowchart that follows five consecutive rules of work which allow a crew to deploy a high-performance framing process is portrayed in the data analysis chapter. The process of developing the rules and the flowcharts representing their application followed three steps:

1. Asking experts in the field to superimpose their opinion with the development of the rules that go into the flowchart
2. Watching the video captures and transcribing the flowchart procedures until final flow was acceptable
3. Reading the operations’ “script” and continuously searching for patterns

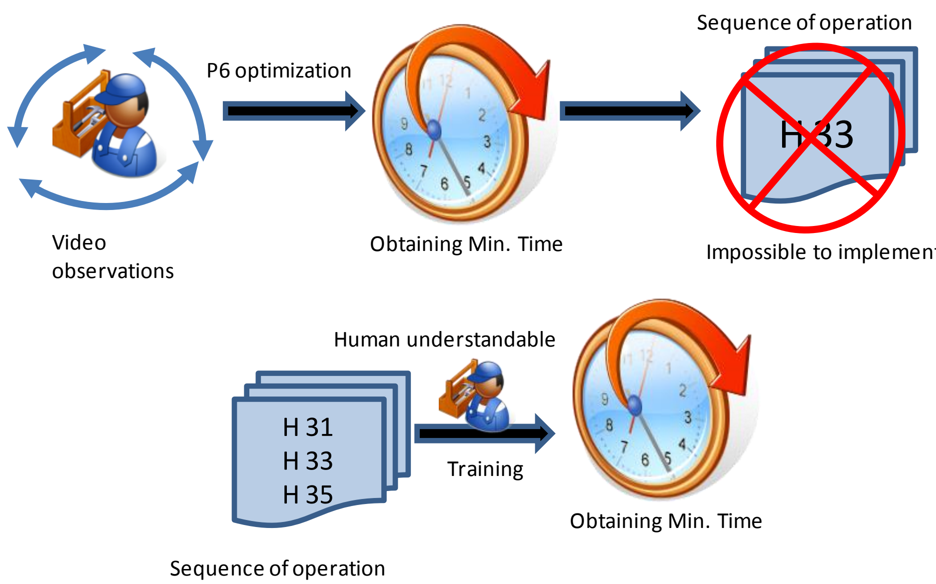

Figure 10. Procedure for development of the flowchart

5.5 Description of Rules and Flowchart

A precedence network was created for scheduling tasks in each frame. The network was then run on Primavera (P6) to calculate the total production time with each of the leveling options (Maghiar et. al., 2010). For this project, the results obtained from the Late Start leveling option for two framers was analyzed to maintain consistency with the actual execution. Therefore, the minimum possible duration using P6 was obtained in each case study.

A flowchart is a diagram that produces the sequence of operations/steps to be followed. The flowchart in consideration is a valid attempt to understand and reflect the mental model of framers with an emphasis on productivity, safety and quality. Comparison of task sequence, constraints and errors (observed on site) for each frames were analyzed to derive finally at the five rules and their sequence in the flowchart.

In the process of flowchart development the three steps mentioned in the previous section were continuously recalled. Initially, all the video observations in the case studies revealed the fact that framers are working around some types of enclosures like windows, doors or the whole frames. This fact was believed to be the first rule: work on [“jig-core”] first. Then, one experienced framer would take tasks as many as possible to work on, the so-called “complicated elements” by considering making sub-assemblies or by using tools repetitively on multiple elements. On the other hand, other framers’ behaviors suggested preference to work more on the “similar elements”, the ones that have similar and repetitive tasks to execute. That would represent the third rule as was considered later in the process of developing the final flowchart. For tasks with unreleased constraints that were not executed for certain elements in the frame, the consideration of leaving into a "mental stack" for later execution was taken into account. The "mental stack" procedure was then followed as a valid rule because of the remaining tasks unexecuted for the elements that were started, but not finished. One question was addressed immediately: How many steps ahead does one think? Later observations showed a relative inconsistent pattern of one framer undertaking tasks for work to unfinished elements worked by the other framer to a certain point in time (taking tasks from others' pool of tasks). Another inconsistent pattern discovered was in the way the framers would select the walk in order to "pick up" the next available task or element to work from his current position (location where the actual task was just executed by the framer). This was considered later a rule in which the selection of the minimal walk is in the mind of all framers. Another question aroused to assess how far one framer would move from another in order to be safe and productive and to not impede others' safety and productivity.

To reiterate, the following seven rules were initially believed to construct the flowchart:

1. Jig-core first
2. Complicated Element, by working on subassemblies or by working on element with greater number of tasks
3. Work on similar elements together
4. Mental stack procedure

5. Stay with element

6. Select minimal walk

7. Move away from any other framer

In the process of refining, going from the very first study to the last one, it was believed that a rule pertaining to the safety of executing any task one would select was necessary to be implemented in the flowchart. Because rule 7 (as mentioned above) was discovered implicit as an automatic derivation of rule 6, it was eliminated later. All pertaining tasks to elements making up the "jig-cores" (windows, doors or the whole frames) are practically executed when a framer would work on the complicated elements and/or similar elements (rule 2 and 3, in the initial consideration). As a result, the need to eliminate rule 1 became obvious. Therefore, the final 5 remaining rules were placed into the flowchart and logical connections for programming and automation were carefully depicted after reading again the operations' "script" and all discovered patterns in framers' behavior were analyzed. A final flow in the external flowchart was achieved through numerous iterations on all four studies and the mental stack procedure was developed as the internal flowchart (see final version in Figure 11 and 12).

To assert consistency while allocating the five rules, they were clearly defined as follows.

<u>*Rule 1*</u>: *Complicated Elements* - Any element that requires two or more measures and marks, tape measures or in-situ measurements is considered a complicated element for the purpose of this study. Emphasis was laid on measure and mark as it dictates the dependency of other elements. The formula created for

determining if one element is complicated based on the number of tasks needed to be performed on the respective element is provided below:

$$CE_{XX} = Max\ [0, \sum (M\ XX\_YY) - 2] \qquad [1]$$

Note that once explained the concept, people have an innate ability to identify complicated elements without having to perform the calculation. The formula has its use mainly for automation of the activity sequencing and for maintaining consistency in the validation of the results.

For instance, in the second Frame, E16 is complicated as it has more than two measures and marks; M 16 03, M 16 04, M 16 05, M 16 06, M 16 07, M 16 08, M 16 09, M 16 10, M 16 11, M 16 12, M 16 13 are all actions performed on E 16 and act as constraints on E 03, 04, 05…13 because P 03, P 04…..P 13 cannot be performed due to the precedence rule. Also, it was noted that error on a complicated element would have adverse impact on the overall productivity and quality of the frame. For instance, in Frame two, an error in placing E 33 resulted to an error in placing the entire dependent tasks on the whole frame (such as E 03, 04….13) and required multiple handling; thereby, affecting the overall productivity and quality of the whole teamwork.

<u>Rule 2</u>: *Safety* - A task is considered safe if a framer continues to work on his current element/ element's as long as possible and is at considerable distance from the other framers. A framer is also considered safe if he can avoid tool related hazard and keep the protective equipments (hard hats; boots, etc.) on through the course of the operation. In this research, no safety hazards were encountered. It was believed that this rule was essential purely from a safety

perspective and did not have a direct relation to productivity and quality of the Frame.

<u>Rule 3</u>: *Similar Elements* - Two or more elements are considered similar if they are of the same length and can be interchanged. For e.g. in Frame two, E 08 ≈ E 09 as they are of the same length and interchanging the position of the two studs will have no adverse affect on the overall outcome of the Frame. In addition, complicated elements are viewed similar if A ⊆ B (Element A≈B if A can be a part of B) and has a maximum of one cut difference. For e.g. E 33 ≈ E 16 as E 33 can be a part of E 16 and E 16 is only one cut different from E 33. The rule was taken into account as it was believed that performing a similar task on similar elements will help reduce errors and improve productivity. For instance in Frame two, it's easy and effective to work on E 23 and 24 simultaneously as they have the same length and need the measure, mark and cut.

<u>Rule 4</u>: *Minimal walk* - Minimal walk refers to the shortest travel distance needed to perform (Place) the next task from a framers' current position. It was assumed that this will help reduce the unproductive travel time. This research doesn't include travel distance needed to bring the material (lumber) or tools (nails, saw-cut machine or the nail-gun machine) to the job execution area.

<u>Rule 5</u>: *Stay with the Element*: This rule defines the need to execute all possible tasks on the current element and make a conscientious effort to return to the element and execute the remaining tasks at the earliest possible opportunity (when all previous constraints in place are released). This rule was intended to reduce the burden of requiring framers to remember the task while improving

productivity and quality. If framer one is assigned E XX, he/she is expected to perform all the tasks associated with it. However, it was believed that if a task is related to two or more framers (hindered work - specifically N XX_YY), it is not considered the responsibility of the framer who initiated the work on that task (E XX or E YY).

Are these five rules sufficient and necessary? To test the necessity and sufficiency of these rules, they were embedded in a flowchart and each individual frame was run through the flowchart. Multiple iterations were performed to understand the position of these rules in the flowchart and until a smooth flow of the entire executed work in each study was achieved.

Furthermore, the total production time for the sequence obtained from the five step (five-rule) framework was compared to the total calculated minimum possible time (Late Start leveling principle) obtained using P6. The results of the five rules were then compared to the ideal time as calculated in P6 (late start). Table 12 shows the results of this comparison for each frame and the percentage of deviation. Based on these results the researcher concluded that the five rule approach is a good approach to calculate the ideal execution time.

Table 12: Comparison of the Production Times with Ideal Case

Duration-two framers (1 helper)	Frame One	Frame Two	Frame Three	Frame Four
Five-rule Framework	200 seconds	504 seconds	418 seconds	472 seconds
P6-LS priority rule optimization	198 seconds	514 seconds	399 seconds	466 seconds
Deviations	1.0%	1.9%	4.7%	1.3%

If one of the rule is taken out from the flowchart (e.g. the complicated elements - rule 1, as defined above), the whole logic of the flowchart collapses. It will become technologically impossible to acquire and execute some of the tasks that are essential for all frames. Therefore, the flowchart (internal and external, see Figure 11 and Figure 12) was deemed to be the most condensed version and possible to implement on site, without creating haphazard situations for framers and with the minimum contained and functional number of rules. So, the five rules became self-sufficient for all frames.

Though P6 optimizations are ideal (for robotic implementation) for all frames, the sequence when analyzed thoroughly was not easy to comprehend for direct implementation for framers on the jobsite. However, the production time obtained from the five-rule framework exposed the researcher to a valid model of crew coordination that is more efficient than the actual coordination witnessed on the jobsite.

5.5.1 Element and Task Focused Work

Understanding the mental model from the perspective of one framer involves addressing the following questions:

- What exactly are we building as a team?
- How are we building it (from planning principle point-of-view)? For example: why preassemble certain elements together? How to make decisions in regard to the assembly of certain studs, etc.

Executing the mental model that transfers one framer's work into a section of the finalized wood-frame involves understanding precisely two facts:

- What are we building and when (a time-sequence procedure that assures quality control of the work)
- How are we building, which requires a particular skill specific to the task and knowing in advance what one should do next, that assures productive and safe work for oneself and others in the team

The framers should focus on the distinction of their mental framework procedure to assure workflow. Based on the video observations, consultations with construction experts and the results of the developed methodology for this study, it is concluded that framers either focus on completing the actual tasks by using mainly a tool-based focus or by using an element (stud) based focus. The element based focus is basically an assigned-to-element "mental pool" of tasks that need to be performed efficiently until a final position of the stud in the frame is secured.

5.5.2 Craftsmanship versus Automation of Task Execution

When analyzing the tasks and their elements to check on the possibility for automation and integration into an existing modeling software tool, there are two possible directions the research can take:

- Industrial setting (for automation, where all tasks should be performed in an organized, planned and executed manner that assures maximization of production) → manufacturing environment. In this environment the rule 5 "stay with the element" would probably be replaced by "stay with the tool". This setting is setting is characteristic of the prefabrication plants.
- Craftsman setting (to keep the actual framers and use their skills and provide an effective mental model to assure maximum efficiency, but accounting for safety and quality of the work produced) → jobsite, artisan setting. This setting, where the craftsman "stays with the element", reduces the need to plan ahead too far and gives pride of accomplishment for craftsman. The research focuses on the craftsman setting only.

5.5.3 Crew Size Determination and Optimum Performance

An algorithm to create an automated way of generating the optimum number of the framers for a crew that performs construction of a frame with a determined geometry (with a certain complexity) is presented in the following chapters. Also, implementation into a Building Information Modeling (BIM) tool is correlated with the crew sizing for various frames and a procedure to extract the BIM information in order to determine the exact number of the framers in a particular crew is explained further in chapter 7.

5.5.4 Assigning Rules to Elements

Based on the definitions of rules in the methodology, the following two steps were performed prior to running the tasks in the flowchart:

- Step 1: Identification of elements as Complicated or Simple (Rule 1)
- Step 2: Grouping elements based on similarity as seen in Table 13 below (Rule 3)

Table 13: Rules Applied to Frame Two

Rules based on definitions	Elements – e.g. **Frame two**
Complicated Elements	E 16, E 33 (E 02 + E 01)
Similar Elements	E 16 ≈ E 33 (E 02 + 01) E 17 ≈ E32 ≈ E 18 E 30 ≈ E 31 (E 15 ≈ E 19 and E 14 ≈ E 20) E 23 ≈ E 24 E 03,04,05,06,07,08,09,10,11,12,13,21 and 22 are similar

5.5.5 Development of the Mental Model for Wood Framers

When developing the flowchart representing the way the five rules apply, it was noticed that the flowchart tends to separate into two areas: an outer flowchart and an inner flowchart.

The outer flowchart represents an efficient flow of work to build the frames and appears to be an accurate and descriptive mental model of a framer's work that would lead to a final product (a wall in the actual building). The actions in the outer flowchart are readily observable. The inner flowchart represents the deeper thought process of the craftsman, including elements that are in his memory. The results in the inner flowchart can only be guessed, but the results of the decisions (and hence deviations) are observable.

5.5.5.1 Cognitive Task Analysis - Measurement and Evaluation

According to Crandall et. al. (2006), CTA analysis may show that more experienced commanders can make faster and better decisions. So, the designers of the system may try to compare decision speed (quantitative) and ratings of decision quality (quantitative/qualitative) with and without the new system. Authors also suggest that CTA studies can capture expert-novice differences, and trainers can convert these differences into measures, called “progress markers.” CTA data can also demonstrate what kinds of errors people make and the findings may be able to suggest context-specific measures of performance.

This is exactly the case of the framers in each case study. Discovering the mistakes and errors in each individual case, the trainers can have a more specific basis for their observations and measurements. In this sense, they can noticeably improve the performance through:

- Better decision making
- Better planning
- Better adaptability
- Better coordination
- Better situation awareness

5.5.5.2 The Five Rules Framework

The creation of the rules and their refinement produced a craftsman model of a five rules framework for the erection of a frame. The assignment of productivity rules to task execution is considered later in the validation of the results chapter. The matching of the individual framer's coordination skills with team tasks is performed in order to see how they superimpose their coordination in execution with the developed model (inner and outer flowchart).

5.5.5.3 Mental Model Flowcharts and Shared Work Entailments

The creation of the flowcharts to better comprise the framers' work is completely described in the next sections. The synthesizing of the field work produced by framers was tried repetitively to account for a naturalistic decision-making processes based of the flowchart rules ranking and deployment. Experts in the field agreed with the idea that development of expertise in wood-framing work comes as a collection of the production rules. Their opinion reflected the complexity of the "shared team tasks" concept in making a crew efficient from all points of view. There is an imperious need to address further the concept of applying team task to the work of individuals in a team, in any construction trade; therefore, a series of studies can be developed following this work and the pertaining methodology.

5.5.6 Outer Flowchart

The outer flowchart (Figure 11) helps answer the two key questions below:

- Which Element should I (framer) first pick to execute or work on?

- What should I work on next so that my work will not hinder the other team members?

The outer flowchart is comprised of four rules:

1. Is the Element in consideration “Most Complicated”? This question helps identify the element that needs to be picked to be added in the framer’s mind list. If there are no complicated elements, the framer is faced with varied options to select the next possible element and task. In this situation, on what basis would the framer decide which element to execute?
2. Minimal Walk: This rule helps the framer decide the next Element to pick once all the complicated elements are added to the framer’s mental list.
3. Once an element is decided, the question, “Are there other elements similar to this element?” helps add similar tasks from similar elements
4. The question, “Are there more tasks for these elements?” allows one to add the next predecessor task associated with this element one at a time to ensure that no task is missed

All these “external” rules actually helped the framer to bring about more work and to execute the work in a timely fashion.

The outer flowchart represents an actual awareness of others’ actions to one framer, so it can be considered the influence from “outside” of one framer’s activity.

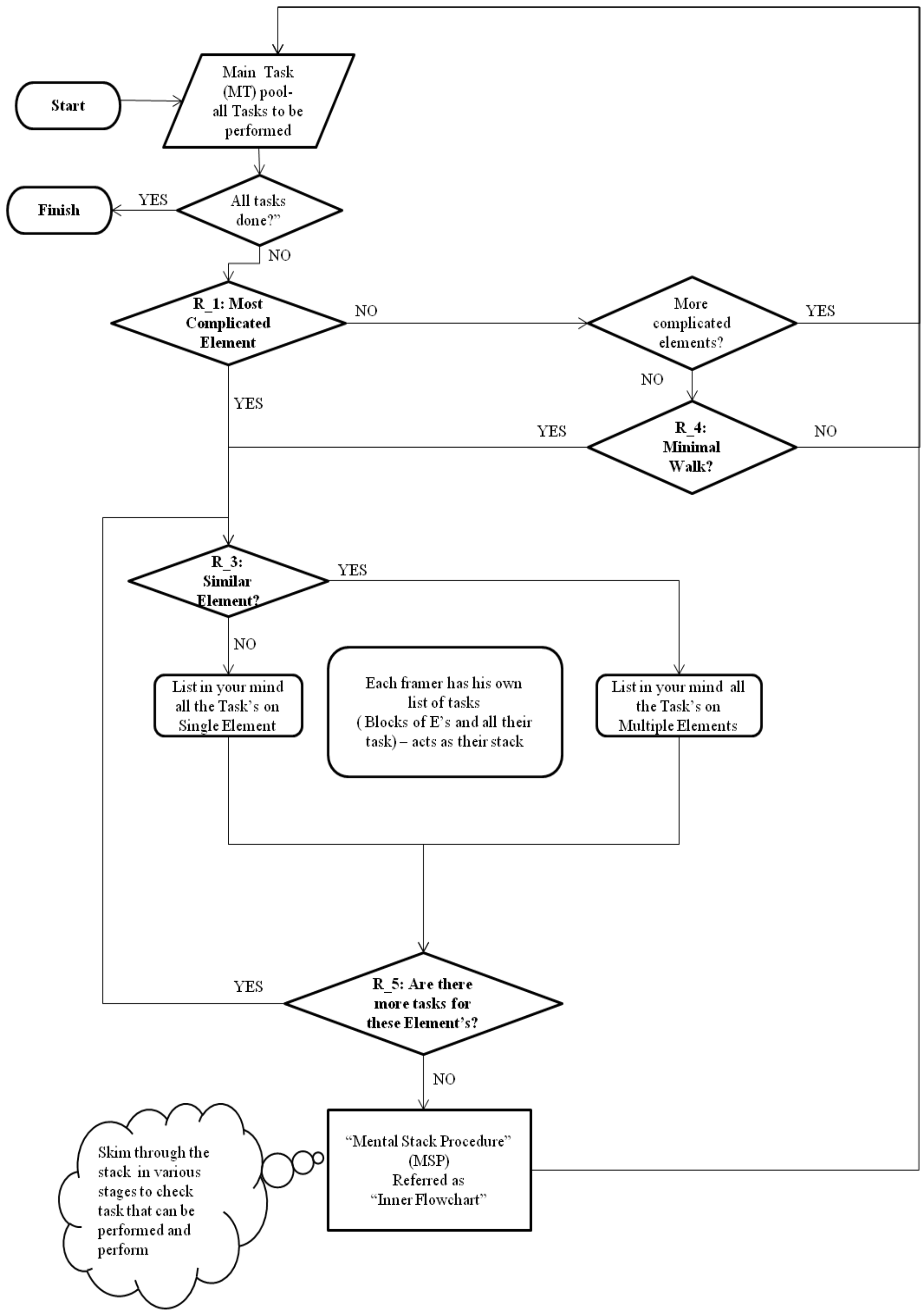

Figure 11: Outer flowchart

5.5.7 Inner Flowchart

The Mental Stack Procedure (MSP) requires multiple decision points as seen in Figure 12. This is referred to as the inner flowchart. This inner flowchart reflects the actual execution of the task from the MS pool of the framer created in the outer flowchart. It demands the need for the framer to skim through the mental stack and perform a task as soon as the following three constraints are released:

1. Predecessor: are all its predecessors complete?
2. Safety: is it safe to perform the task?
3. Minimal walk: Is it at a minimal walking distance from his/her current position?

The internal rules are actually preventing the work to be executed to a series of "filters", like predecessors complete, safety rule being satisfied, minimal walk for the next task to be executed. The inner flowchart is perceived in the framer's mind as the actual awareness of his/her own actions and it happens at the level of each individual.

Once all three conditions are satisfied, the task can be executed and exhausted from the pool. Having that said, if a task satisfying the above three conditions is not performed, does not necessary mean it is a violation of the rule. A framer's decision to execute the task varies based on site conditions and the complexity of that individual frame. However, this research did not focus on how these internal sequence violations could be addressed. Therefore, it is a possible scope for further research. The case of violations in all frames is treated separately in the process of flowchart validation for all case studies.

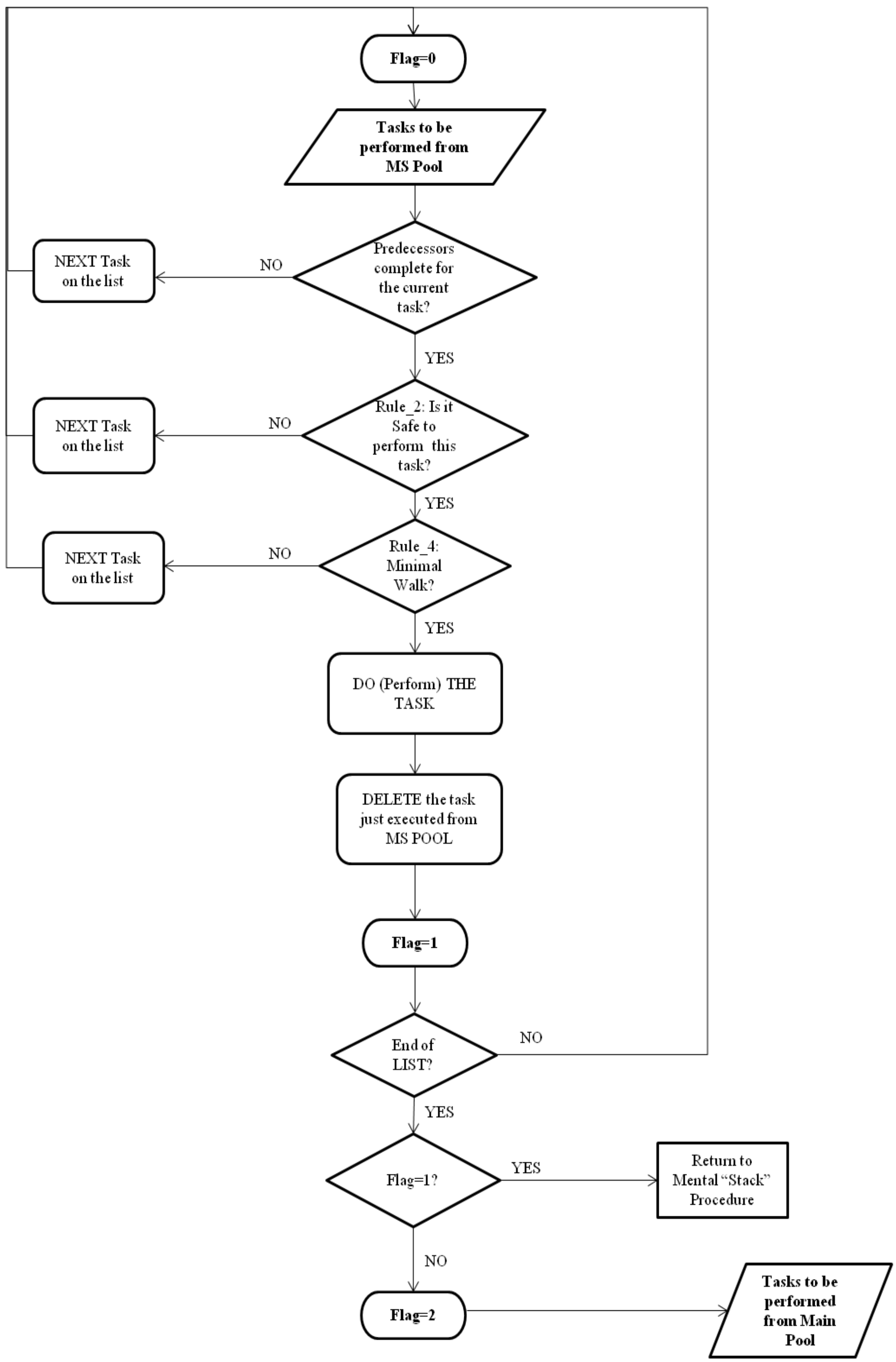

Figure 12: Inner flowchart

Chapter 6

VALIDATION OF RESULTS

This chapter focuses on the validation of the five rules framework model for framing. The five rules framework is a team level mental model developed to serve in crafting the process flow at micro level (tasks) for all wood framing operations. The validating data were collected and analyzed from all four different residential project sites to authenticate the functioning of the model.

Validation of the flowcharts for a wood framing operation was done using the principle of consistency and repeatability in the data collection. This framework model was also created to lay the foundation for better understanding the congruence between individual and team level mental model of any of the construction trades and to maximize their performance to enhance team productivity, quality and safety. In the validation, an attempt is made to illustrate how the cognitive-based flowchart can be implemented in the field of light wood-framing to enhance jobsite productivity. The results of this research also validate the idea that full automation of micro-scheduling is possible and will provide a further avenue to test the feasibility of this study on different construction trades.

6.1 Validation of Outer Flowchart – All Case Studies

As seen in Figure 11, the outer flowchart starts with the main task pool (MT pool). This task pool comprises of all the tasks needed to erect the Frame. For instance, in Frame two the MT pool is comprised of 149 tasks (see appendix C, Table C10). The first step is to pull a task from the MT pool. For instance, if H 01 is pulled from the MT pool, it is run through the first decision point - Rule 1: Is it the most complicated element? Since element 01 is not the most complicated element (element 16 is), it is reverted back to the MT pool. This rejection of elements continues until the most complicated element (16) is selected. It is worth noting that this iteration is a computational approach rather that a human approach. The human equivalent of this iteration is "scan for the most complicated element". Now that element 16 was selected, H16 is pulled from the MT pool and run through Rule 1: Is element 16 the most complicated element? Since it is the most complicated element, it is passed through the next decision point, Rule 3: Are there similar elements to element 16? From the Table 13, it is known that E 33 ≈ E 16. Since E 33 = E 02 + E 01, H 02 and H 01 are added to the framers mental stack (Figure 13- phase 1). The list of elements then addressed the next decision point, Rule 5: Can you continue to add more tasks associated with these current elements to the mental stack of the framer? If yes, it forms a loop with Rule 3. Now P 16, P 02 and P 01 are added to the mental stack (Table 14 - Phase 2) and the process is repeated until all the tasks (H 16, H 02, H 01,P 16, P 02, P 01,N 01 02, M 33 03, M 16 03, M 33 04, M 16 04, M 33 06, M 16 06, M 33 07, M 16 07, M 33 05, M 16 05, M 33 08, M 16 08, M 33 09, M 16 09, M 33 10, M 16 10, M 33 11, M 16 11, M 33 12, M 16 12, M 33 13, M 16 13, M 33 22, M 16 22, M 33 14, M 16 24, M 16 23) associated with these elements become added (from Handle to Nail) to the framer's mind list one at a time. This leads us to the next step, the "Mental Stack Procedure" (MSP). A detailed description of the MSP, referred to as the "Inner flowchart" (presented in the previous chapter) in Figure 12, is offered in the next section. It is worth noting again that this detailed representation in Figure 13 is the programming equivalent of:"I will on the sole and top plates "(elements 01, 02 and 16)

Mental Phase 1	Mental Phase 2	Mental Phase 3	Mental Phase 4	Mental Phase 5	Mental Phase 6	Mental Phase 7
H 16	H 16	H 16	H 16	H 16	H 16	H 16
H 02	H 02	H 02	H 02	H 02	H 02	H 02
H 01	H 01	H 01	H 01	H 01	H 01	H 01
	P 16	P 16	P 16	P 16	P 16	P 16
	P 02	P 02	P 02	P 02	P 02	P 02
	P 01	P 01	P 01	P 01	P 01	P 01
		N 01 02	N 01 02	N 01 02	N 01 02	N 01 02
			M 33 03	M 33 03	M 33 03	M 33 03
			M 16 03	M 16 03	M 16 03	M 16 03
				M 33 04	M 33 04	M 33 04
				M 16 04	M 16 04	M 16 04
					M 33 06	M 33 06
					M 16 06	M 16 06
						.
						.
						.
						M 16 23
						.

Figure 13: Frame two: mental stack for framer one in round one of outer flowchart

6.2 Validation of Inner Flowchart – All Case Studies

The two loops that are constantly running in the minds of effective framers are the MT loop (from outer flowchart, testing rules 1, 3, 4 and 5) and the MS loop (from inner flowchart, testing rules 2, 4 and the predecessors' constraints). The inner flowchart is actually an internal part of the outer flowchart and to validate the flowchart, an example is taken from Frame two; first time a framer skims through the list, he should perform H 16, H 02 and H 01 respectively.

However, in the actual execution H 01 was performed first. This was interpreted as a violation of sequence. Also, H 01 should have been followed by P 01, as all the constraints for P 01 were released. Note that in the Table 14, phase 1, P 01 marked with carets (^) is representing as violation. All the other tasks in the first phase: P 16, P 02, N 01 02, M 33 03, M 16 03, M 33 04, M 33 13......M 16 23 were marked with asterisks (*) meaning that those tasks cannot be performed as the predecessor constraint is not released. This resulted in the need for a second phase. As seen in the Table 14, phase 2, H 01 was removed from the mental stack and H 02 was executed. Note H 16 is still an internal sequence violation. Also, having executed H 02, the framer should have executed P 02 (all constraints released) and removed from the list. As P 02 was not executed even though all constraints were released, it is considered a violation of sequence. In the third phase, H 02 was removed and H 16, M 33 05, M 16 05, M 33 08, M 16 08, M 33 09, M 16 09, M 33 10, M 16 10, M 33 11.....M 33 14 were performed. Note that P 16 was not executed as it is deemed to be unsafe. If placed in its final position, it would be a source of hinderance and would result in injuries due to tripping and falling. When scanned the fourth time, M 33 03, M 16 03, M 33 04, M 16 04, M 33 06, M 16 06, M 33 07 and M 16 07 were all performed and removed from the MS pool. In phase 5, P 01 was performed but N 01 02 cannot be performed due to predecessor constraint (its predecessor are P 01 and P 02). However, it was released of the other two constraints – being safe to perform and was at a minimal walk. In phase 6, once P 02 was performed, N 01 02 was not executed, hence it is considered a violation.

The process (a certain number of phases) was repeated until all possible tasks were performed and removed from the mental stack created in the outer flowchart. Note that each task was analyzed and assigned a code from the legend to understand the constraints it faced. As seen in Table 14, after passing through the list seven times, four unexecuted tasks still remain in the MS pool. As mentioned earlier, P 16 cannot be performed due to safety reasons. M 16 23 and M 16 24 had predecessor constraints. However, N 01 02 satisfied all three constraints but was not executed. Hence it was considered an actual violation.

Table 14: Frame Two: Mental Stack for Framer One in Round One of Inner Flowchart

Mental Phase 1	Mental Phase 2	Mental Phase 3	Mental Phase 4	Mental Phase 5	Mental Phase 6	Mental Phase 7
^H 16^	^H 16^	H 16	#P 16#	#P 16#	#P 16#	#P 16#
^H 02^	H 02	#P 16#	^P 02^	^P 02^	P 02	^N 01 02^
H 01	*P 16*	^P 02^	^P 01^	P 01	^N 01 02^	*M 16 23*
P 16	^P 02^	^P 01^	*N 01 02*	*N 01 02*	*M 16 23*	*M 16 24*
P 02	^P 01^	*N 01 02*	M 33 03	*M 16 23*	*M 16 24*	
^P 01^	*N 01 02*	^M 33 03^	M 16 03	*M 16 24*		
N 01 02	*M 33 03*	^M 16 03^	M 33 04			
M 33 03	*M 16 03*	^M 33 04^	M 16 04			
M 16 03	*M 33 04*	^M 16 04^	M 33 06			
M 33 04	*M 16 04*	^M 33 06^	M 16 06			
M 16 04	*M 33 06*	^M 16 06^	M 33 07			
M 33 06	*M 16 06*	^M 33 07^	M 16 07			
M 16 06	*M 33 07*	^M 16 07^	*M 16 23*			
M 33 07	*M 16 07*	M 33 05	*M 16 24*			
M 16 07	*M 33 05*	M 16 05				
M 33 05	*M 16 05*	M 33 08				
M 16 05	*M 33 08*	M 16 08				
M 33 08	*M 16 08*	M 33 09				
M 16 08	*M 33 09*	M 16 09				
M 33 09	*M 16 09*	M 33 10				
M 16 09	*M 33 10*	M 16 10				
M 33 10	*M 16 10*	M 33 11				
M 16 10	*M 33 11*	M 16 11				
M 33 11	*M 16 11*	M 33 12				
M 16 11	*M 33 12*	M 16 12				
M 33 12	*M 16 12*	M 33 13				
M 16 12	*M 33 13*	M 16 13				
M 33 13	*M 16 13*	M 33 22				
M 16 13	*M 33 22*	M 16 22				
M 33 22	*M 16 22*	M 33 14				
M 16 22	*M 33 14*	M 16 14				
M 33 14	*M 16 14*	*M 16 24*				
M 16 14	*M 16 24*	*M 16 23*				
M 16 24	*M 16 23*					
M 16 23						

LEGEND
$___$ Is not min. walk
___ Predecessor not complete
#___# Is not safe
^___^ Is a Violation
~___~ Is a Task from other framer's pool
(shaded) Executed task

The list of actual task execution sequence for this frame is given in appendix C. In appendix D, detailed tables show for each case study the list of tasks with their predecessors, duration assignment and notes for the first case study (reasons provided to explain the deviations from average duration of the task type).

Returning to Table 14, we are now focusing on the final mental phase (phase 7). This phase contains a list of the tasks that cannot be executed. This list (kept in the memory of the framer) is placed in what we call “the mental stack”. This stage is represented as backlog, as “stage one” in Figure 14. Once a mental stage is added to the mental stack the inner flowchart leads back to the MT pool in the outer flowchart. A new set of elements is now pulled from the MT pool in this case; E 03, E 04……E 21 and E 22 and the entire list of task is added to the Mental Stack procedure, one task at a time. In the Mental Stack Procedure, these new set of elements (and all their tasks) are added below the backlog tasks from round one. For convenience, each time a new set of elements is extracted from the MT pool, it is named as Stage 1, Stage 2, Stage 3, etc. as seen in Figure 14 and Figure 15. Note that after executing H 03 (Figure 14, Stage two) the framer executed P 03 rather than H 04, H 05, etc. The framer’s decision to place P 03 was justified as being a minimal walk when compared to performing H 04. The process presented in the flowchart is repeated until all the tasks from the pool are removed. The best case scenario is believed to be when a framer removes all tasks from his mental stack (by executing- inner flowchart) before adding any new elements and its related tasks (called as Stage two) in the mental stack from the MT pool.

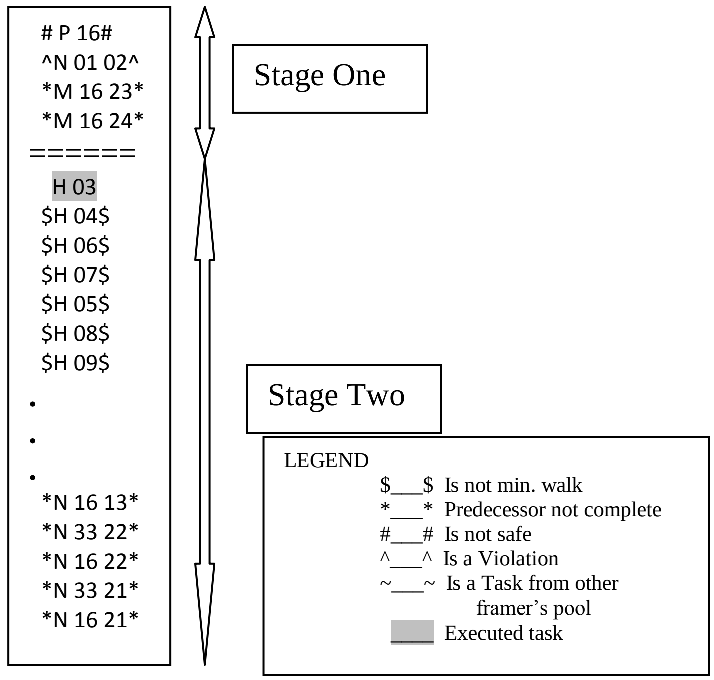

Figure 14: Start of round two

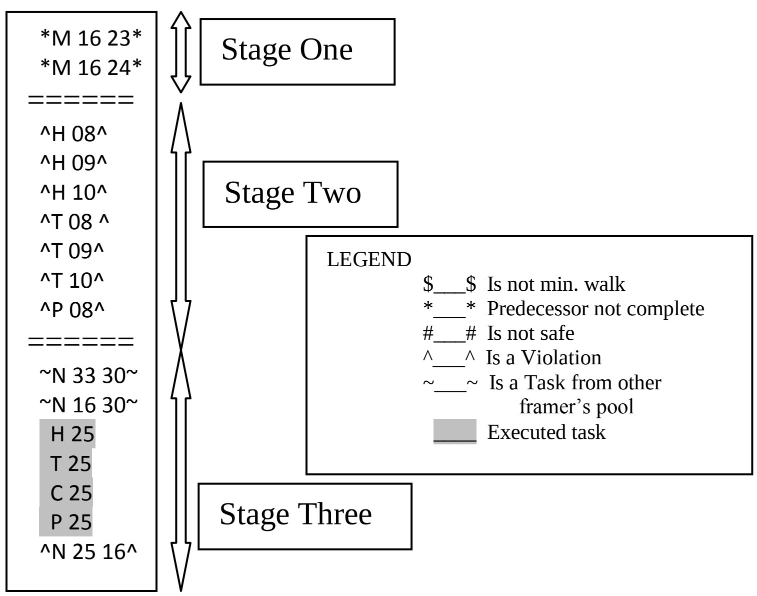

Figure 15: Backlog at the end of round four

In certain cases, framer one performs tasks assigned to framer two. For example, as seen in Figure 15, framer one executed N 33 30 and N 16 30 that were pulled from the other framer's list of task. This was also perceived as a violation due to its possible impact on quality of the product, in this case, the frame itself. It was deemed that switching between elements (i.e. taking activities from the mental stack of another framer) induces a split in the responsibility for the quality of the product and hence has the potential of reducing it. An alternate view that this is a sign of double quality control, is acknowledged here. However, based on the assumption of sufficiency of minimal quality, a decision was made to select the first interpretation. The process presented in the flowcharts was repeated for the second framer to identify his violations (details can be found in the appendix C). At the end of round one, framer two had one violation - P 29. To identify their violations at the end of each round, this process was repeated for each framer in the other three studies as well.

These rounds and phases were manually “filtered” through this process until all the tasks pertaining to each framer in all four frames were executed and the new optimized time was recorded. Therefore the work would have performed by going logically through the flowcharts and reflecting the five-rule framework assignments to each and every task attributed to the framers. The processes were tested independently by two people and produced identical results, thus proving that this approach is consistent and replicable.

Once the five-rule framework sequence was completed for all the four frames, the total production time obtained using this framework was compared to the actual execution time incurred from the video observations. Table 15 illustrates the comparison of the production time in actual execution, five-rule framework and P6-LS priority rule optimization. Figure 16 is a graphical representation of these two production times for all frames in the study.

Note that while the initial development of the five rules was carried out on Frame one using ideal execution times, the validation of flowchart for Frame one was performed with the total actual execution times as witnessed on site. The P6 (LS) optimization showed in the methodology chapter was performed with the times provided in the table of predecessors and durations within the appendix D, along with notes explaining reasons for time tasks deviations as occurred on site.

Table 15: Comparison of the Production Times

Duration-two framers (1 helper)	Frame One	Frame Two	Frame Three	Frame Four
Actual Execution	544 seconds	620 seconds	460 seconds	480 seconds
Five-rule Framework	480 seconds	504 seconds	418 seconds	472 seconds

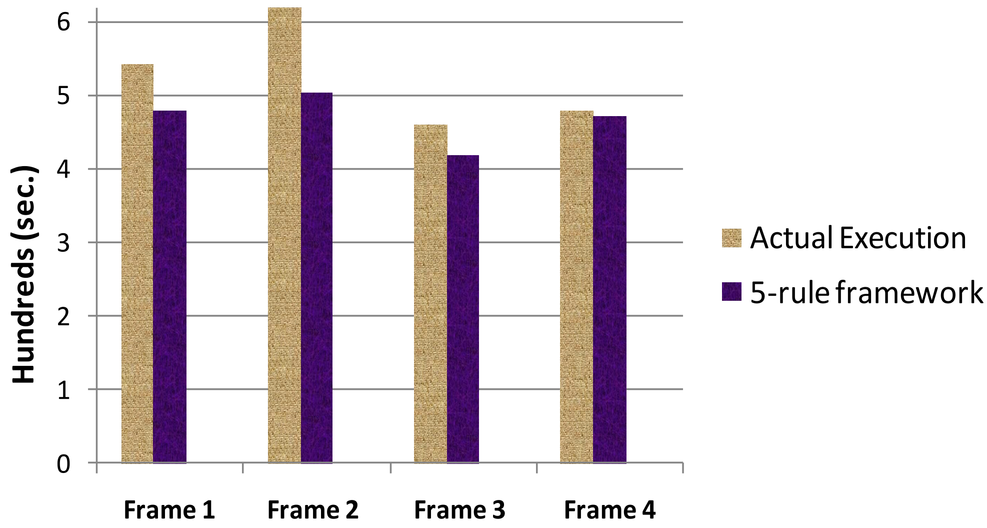

Figure 16. Graphical representation of the production time comparison for all frames

Comparing the actual execution with the five-rule framework, one can notice that the five-rule framework model gave better total production time in all four Frames when compared to the actual execution. This indicates there is definitely a scope for actual productivity improvement based on the sequence opted. All four frames were tested for the inner and outer flowchart and the conclusion was that they reflect the human comprehensible and achievable sequence of work with tendency to maximize performance.

6.3 Consideration of the Framers' Coordination Assignment Within Crew

In the process of assigning tasks to the framers, when the focus was to validate the flowcharts, the actual five rules pertaining to the execution were assigned to the tasks in the process of performance and coordination. These tasks come along with the "external" and "internal" process of a framer's mental model that lead him/her to the execution of that particular task. Table 16 is an excerpt of the assignments for frame 2 conducted by the first framer who is assumed to have more experience than the second framer. The rules which are processed through the flowchart contribute to the execution of the tasks, according to Table 16. For instance, task H 16 (row 3 in Table 16) was selected based on Rules 1 and 3 (outer flowchart) and Rules 2 and 4 (inner flowchart).

Table 16. Assignments of Rules from Flowcharts to All Tasks

Task ID	Duration	Predecessors	5 RULES (Outer flowchart)	5 RULES (Inner flowchart)
H 01	1	S	5	2,4
H 02	2	S	3	2,4
H 16	13	S	1,3	2,4
M 33 05	1	H 02	5,3	2,4
M 16 05	1	H 16	3	2,4
M 33 08	1	H 02	5,3	2,4
M 16 08	1	H 16	3	2,4

It is acknowledged that an experienced framer (“expert”) subconsciously has this knowledge and any violations of not following the checking points (the rules in the flowcharts) can potentially lead to a hazardous situation (safety issues) or a to rework situation (quality and productivity issues toward the future execution of the tasks associated with the next studs forwardly in the process). This does not mean that the experienced framers do not make errors or cause safety hazards. The actions witnessed in all the videotaped activities (in the case studies) revealed errors made by the more experienced framers which led to a direct impact on productivity or quality of work performed by them and overall by the crew. This problem is addressed later in this chapter.

The next step was to establish a rate of compliance (in regard to the procedures-rules followed in the flowchart as one would perform work) for every framer within the crew. This analytical process is a quantitative measurement and it is meant to assess the performance and coordination match in relation with team's tasks (building frames of certain complexity). Matching individuals' coordination and performance with team tasks was sought as the main product to be delivered in this research.

To quantify the rules in the flowcharts and their assignments to the performed tasks, they were counted in the process of validation carried out in all studies. The purpose to develop a system to qualify a framer for following the procedures (rules) in the developed flowchart was mainly to determine the coordination for framers that further will enable them to achieve performance relative to their own crews. Basically, a framer coordination profile is attained and it is representing a tool to better understand how he/she integrates within a crew. For each individual framer in every crew, a rate of compliance was established based on all rounds performed by them until all tasks were depleted from the MT pool. Details for the determining the procedural deviation of the framers can be followed for Frame 2, provided as an example in appendix E along with the other results for all case studies. The calculation considerations are explained further.

From the initial phase to the end phase in each round, the unperformed tasks that were not executed either due the rule of safety or because the predecessors were not complete, were called "legitimate skips." These were accounted separately from the tasks performed during the whole round. Also, if a task was not executed during the round even if it could have been, it was considered an “ignored task”. Ignored tasks were accounted separately in the calculation of the compliance rate.

In this quantification, an in-situ ideal number of rules followed by each framer was calculated as the difference between the total assigned rules in the ideal case (a round where all the tasks from the beginning are executed entirely until the end) and the number of rules assigned for tasks considered legitimate skips. Then, the compliance per each round was calculated as percentage:

$$Compliance = 1 - \frac{Ignored\_tasks}{In\ situ\_ideal}\ [\%] \qquad [2]$$

This compliance (per round) -as percentage- did not take into account the so-called productivity extolments, meaning tasks at the end of the rounds that were not performed because of the minimal walk rule (number 4) or incomplete predecessors that were not satisfied. The safety and quality extolments were the only ones allowed to be considered legitimate skips for obvious reasons. In some cases, because all the tasks per round were executed (MS depleted), the compliance was calculated as 100%. An analysis was conducted for each framer and each round and an average compliance rate (in percentages) was calculated for each individual framer (Table 17). Details of the calculations are shown in Appendix E, Table E1 to Table E13.

In Table 17, Framer 1 is always the “lead framer”-considered to be the expert. This assertion is based on the fact that it is the expert who will start with the most complicated element (Rule 1).

Table 17. Percent Compliance Relative to the 5-Rule Framework

FRAME	Framer	Percent Compliance P(%)
Frame 1	Framer 1 (Red shirt)	92
	Framer 2 (Gray shirt)	86
Frame 2	Framer 1 (Red shirt)	83
	Framer 2 (Gray shirt)	90
Frame 3	Framer 1 (White shirt)	89
	Framer 2 (Blue shirt)	87
Frame 4	Framer 1 (Red shirt)	88
	Framer 2 (Blue shirt)	95

Framer 2 is the "support framer", a novice doing more work on similar elements. The selection was made based on the video observations.

6.4 Matching Coordination with Team Tasks

The actual compliance rate of procedures (P) for individual framers represents their general ability (based on their skills) to follow the rules in the flowcharts and in the execution of the work overall. In order to realize how well the framers are following the five-rule framework, an average procedural deviation was calculated in percentages for each frame, as being:

$$Avg\_Proced\_Dev = 1 - \frac{Fr.1\_compliance + Fr.2\_compliance}{2} [\%] \quad [3]$$

Based on the results obtained, the four frames are organized from the one with the least average of procedural deviations to the one with the highest average percentage of procedural deviations per team. The full results are depicted in Table 18.

The procedural deviation of the worst framer is also calculated as a function of:

$$Proced\_Dev = 1 - Min\,[(Fr.1\_compliance\ \%) - (Fr.2\_compliance\ \%)] \quad [4]$$

To be able to compare these results with the productivity decrease as procedural deviations are encountered in each frame, a percentage of productivity declines (five rules versus actual execution) are calculated based on the actual execution time and the five-rule framework time obtained in every case:

$$Productivity\_Decline = [ABS(\frac{Actual\_Execution\_Time}{5rule\_Framework\_Time}) - 1](\%) \quad [5]$$

Table 18. Procedural deviations and general productivity per frame

Framer/ Frame	Compliance Framer 1 [%]	Compliance Framer 2 [%]	Procedural Deviation of Worst Framer [%]	Actual Execution Time (sec.)	5-rule Time (sec.)	Average procedural deviation [%]	Productivity Decline [%]
Frame 4	88	95	12	480	472	8.5	2
Frame 1	92	86	14	544	480	11	13
Frame 3	89	87	13	460	418	12	10
Frame 2	83	90	17	620	504	13.5	23

The discussion and interpretations of these results is provided in the first and second section of the conclusions chapter.

6.4.1 Coordination Requirements for Performance Maximization

The graphical representations of productivity decline (in percentages) relative to the Procedural Deviation of the Worst Framer – PDWF (in percentages), for every frame, are portrayed in Figure 17.

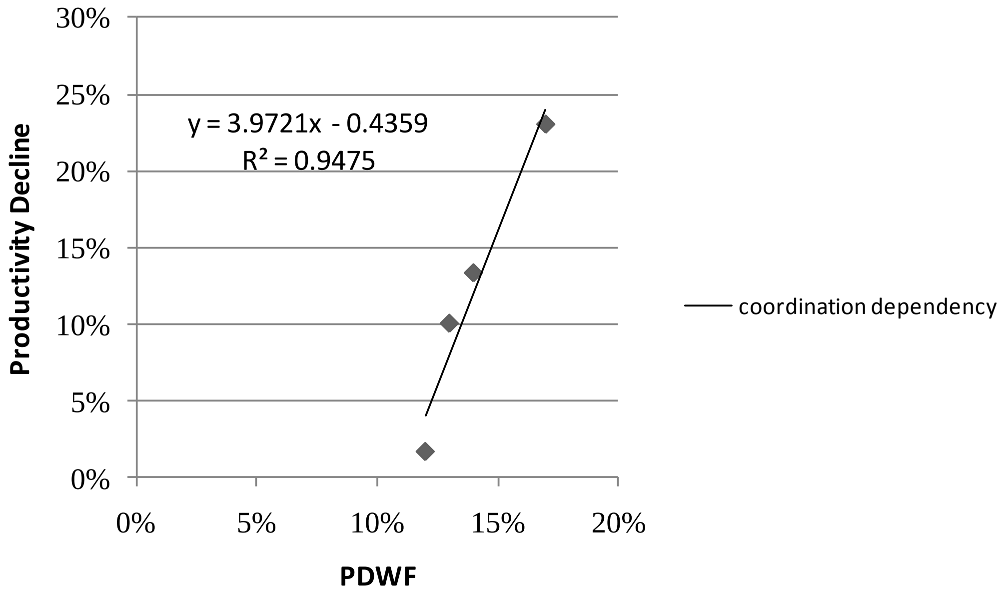

Figure 17. Productivity decrease as function of procedural deviations of the worst framer

The graphical results convey that the requirement for performance maximization is almost linear in nature and is contingent upon the coordination dependencies of framer that abided by the 5-rule framework the least amount of time (in the respective crew). The linear regression trendline was added to the graphical representation and the equation showing the linear dependency between variables. This equation is:

$$y = 3.9721*x – 0.4359 \qquad [6]$$

R-squared value (R^2 = 0.9475, being close to 1) establishes the dependency of the two variables.

The hypothesis that the average procedural deviation will be a predictor of team's coordination is presented in Figure 18. The equation is:

$$y = 3.8738*x – 0.3156 \qquad [7]$$

R-squared value is $R^2 = 0.8529$

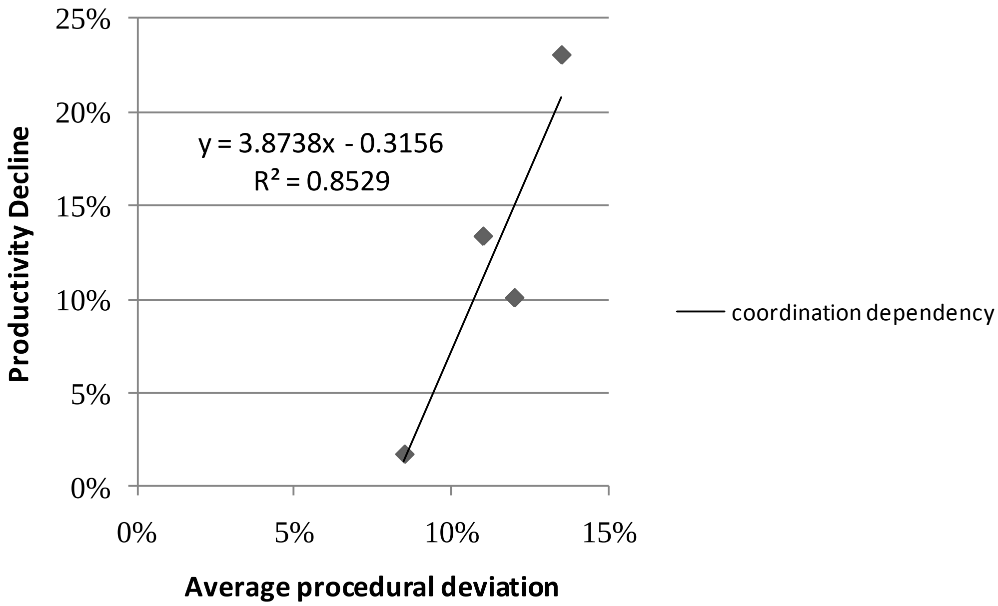

Figure 18. Productivity decrease as function of team average procedural deviations

This fact indicates a higher confidence in the statement that the effectiveness of a crew is influence by the performance of the weakest crew member rather than the average performance of the crew members. It can be concluded that equation [6] represents the influence of individual's mental framework on the performance of the crew. Having a slope of about 4 and an intercept of about 11 %, the conclusion can be stated as: "once the worst framer in the crew surpasses the limit of 11% deviation from applying the said five rules, every additional percent of deviation reduces the productivity of the whole crew by 4%."

Chapter 7

IMPLEMENTATION IN BIM (BUILDING INFORMATION MODELING)

7.1 BIM and Crew Sizing for Wood Framing Work

BIM is an integrated process that allows architects, civil engineers and contractors to look at a project digitally, on the computer screen, before it is even built. The reason to implement the productivity results obtained in the methodology of this research is that through more efficient team coordination, accurate micro-scheduling, and clash-free installation, BIM-driven jobs typically can be built much quicker than jobs delivered using paper based drawings. In regard to trades, it allows for better collaboration and sequencing and eliminates the need to stack trades, which negatively affects every subcontractor's productivity. This can be the case for light wood-framing trade in the commercial and residential construction.

One key factor in the productivity of any construction crew is the way the foreman assigns and organizes the work of each team (for a literature review relevant to this point, see Day et.al. 2007, and Styhre and Josephson, 2007).To make a clearer distinction between the two terms - crew and team - a "crew" is a group managed by a foreman and a "team" is the sub-group that is given specific tasks within a crew. For instance, a crew of framers can have five members and may be split up by the foreman into a team of two and a team of three framers. Experienced foremen know instinctively how to size the teams to ensure maximum productivity based on frame complexity. Unfortunately, with the aging of the construction workforce, this skill of the foremen is rapidly vanishing.

The purpose of the implementation in BIM was to check whether information from BIM models can be used to automatically determine the most effective crew size for construction operations, thus replacing to some extent the vanishing skill of experienced foremen. The whole research study dealt with the wood-framing processes; therefore, selection for implementation was wood framing as a test case. This decision was motivated by two factors:

(1) most BIM programs (such as Autodesk Revit or ArchiCAD) already have the capability to automatically design and represent all the elementary components (studs and plates) of wall frames; and

(2) access to jobsites where wood framing was taking place for observations and reality comparison is easily obtained and it was already carried out.

Determining the exact size of a team based on the information available in BIM software can be done quite simply. Most of the BIM software can represent each component of the wall frames down to the level of studs and plates. Automatic routines are available to complete such representation if the designer has not yet completed the design to this level of detail. For the purpose of this determination, the information about the parts and elements was considered available. With this in mind, the following four goals were set:

1. Evaluate the possibility of automatically creating tasks and task sequencing from BIM models
2. Seek the influence of the resource leveling criteria in P6 on team productivity for further consideration to implementation in BIM
3. Test the possibility of team sizing without using P6 optimization algorithm

4. Recommend an implementation procedure for team and crew sizing using BIM

Although the determining of crew sizing based on frame complexity and productivity levels was considered as a “spin-off” research of crew performance skill-set modeling, it has implications in the use of cutting-edge technology tools, such as BIM software, in today’s construction industry.

Initially, a productivity loss dependency matrix was created based on the total number of tasks and the number of framers in the team. The productivity loss was calculated using the best-case scenario (LS resource leveling). The duration for each frame in the LS resource leveling was taken into account as the calculation was performed increasing the numbers of framers to each crew in every single frame. The matrix and the three-dimensional graph representing the matrix are depicted in Figure 19 below. One framer represents the baseline as, theoretically, there is no loss of productivity owed to coordination. To ease the reading of the three-dimensional graph, the single framer was omitted. The productivity loss dependency matrix allows us to automatically determine the maximum size of a team based on the size of the accepted loss of theoretical productivity. For instance, if a 2% loss of theoretical productivity is accepted by a foreman or superintendent, then the maximum number of team members is as follows: Frame 1 – 1 framer, Frame 2 – 2 framers, Frames 3 and 4 – 3 framers.

Frames

Framers	**Fr. 1** *119 Tasks*	**Fr. 2** *149 Tasks*	**Fr. 3** *203 Tasks*	**Fr. 4** *343 Tasks*
1 Framer	0%	0%	0%	0%
2 Framers	3%	**2%**	1%	1%
3 Framers	6%	3%	**2%**	**2%**
4 Framers	8%	5%	3%	3%
5 Framers	11%	12%	7%	4%

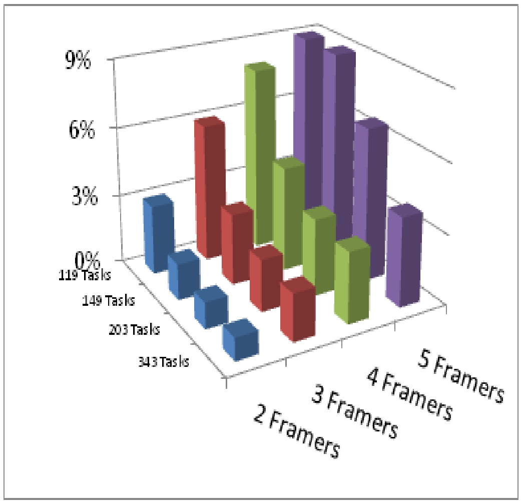

Figure 19. Matrix of different productivity levels and framer availability (with known number of tasks)

It is assumed that real-case productivity will be proportional to the calculated productivities; but at this stage, there is no empirical proof of this statement for teams consisting of more than three framers. The largest teams observed had three members: two framers and a helper. This observation is leading us to believe that the total accepted loss of theoretical productivity is about 2%. Using 2% as a guiding number, the method described above can easily be implemented to size the teams for framing. The guiding principle presented in Table 19 is that the number of team members is a *step function* of the total number of tasks required to build the frame. The critical number of tasks is 200, since below 200 tasks, the step function shows one or two framers, whereas above 200, the maximum team size is 3 framers. A close approximation of the total number of tasks can be obtained by multiplying the number of components by four (each component has Handling, Measuring, Cutting and Placing), adding two more tasks for each point where two components meet (for Marking and Nailing), and then subtracting twice the number of full-length studs, for they have no Measuring and Cutting (equation [8]):

$$T\_tasks = (Xstuds) * 4 + (Ycontact\_po\ int\ s) * 2 - (Zprecut\_studs) * 2 \quad [8]$$

where T_tasks is total number of tasks for a given frame, X represents the number of studs comprising the frame, Y is number of contact points given in the actual geometry of the frame and Z represents the numbers of studs that are brought precut to the jobsite.

For instance, Frame 1 has a total of 19 components and 32 points where components meet (11 vertical components induce 22 points and 5 horizontal components induce 10 more points). Six (6) of these components are full-length studs. The simplified calculation for the total number of tasks in frame 1 is: 19 * 4 + 32 * 2 – 6 * 2 = 128 tasks (compared to the 119 tasks that were observed in the video recording). The difference between the calculated total number of tasks and the total tasks observed in the video recording is coming from the fact that typically framers are handling multiple elements together (up to about four) in the beginning of the work and therefore there is no additional handling for each individual stud in the proximity of the work area. Based on this formula, the team can be sized as shown in Table 19.

Table 19. Team Sizing as a Function for Number of Tasks

Number of tasks	≤120	≤200	>200
Maximum Team Size	**1**	**2**	**3**

7.2 Extraction of BIM Related Information to Determine the Number of Framers in Crews

All data required for formula [8] is easily obtainable from the BIM model and, thus, it is possible to determine the size of the team for any particular frame. The actual number of studs is extracted from Autodesk Revit Structure software with MWF (Metal Wood Framer) “add-in” feature which automatically generates the stud arrangements (spacing and location of all studs).

In light-gauge steel framing, MWF is a plug-in that adds the ability to create framing based on specialized parametric relationships that can affect the connections and types of members. For further details see http://www.strucsoftsolutions.com/mwf.asp (June 14, 2011).

The main features that MWF automatically generates are:

- Extra studding around openings based on user defined preferences
- Internal and external sheathing, bracing and extra studs
- Kickers and Equipments backing members
- Automatically assigns panel numbering and shape labeling
- Fire stop assemblies schedule, etc.

An example of generated non-bearing wall panel for a residential project is given in the Figure 20, with all annotations and dimensions of studs and headers provided for the users.

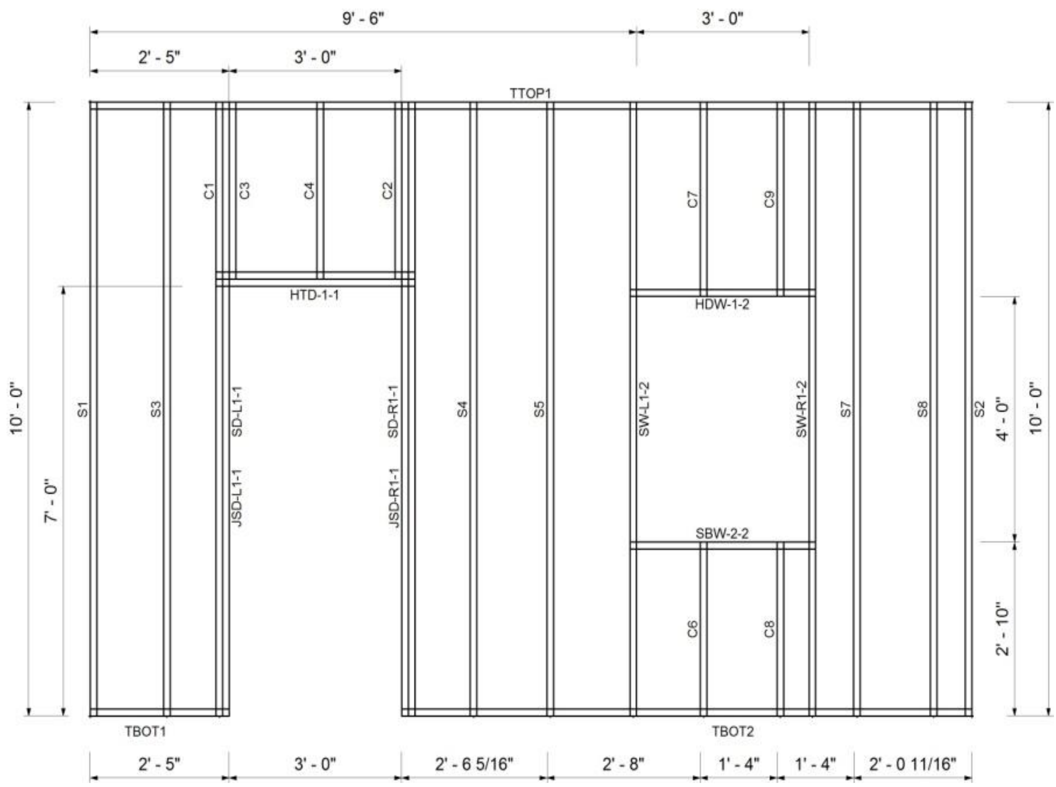

Figure 20. Automatically generated panel for a stick frame residential construction

The process of generating the frame and obtaining the total number of studs from a generated frame is illustrated in Figure 21 and Figure 22, below. Currently, MWF provides the breakdown of the studs (king studs, jack studs, headers, sole and bottom plates, cripple studs, etc.), which are then counted to obtain the total number of studs per frame.

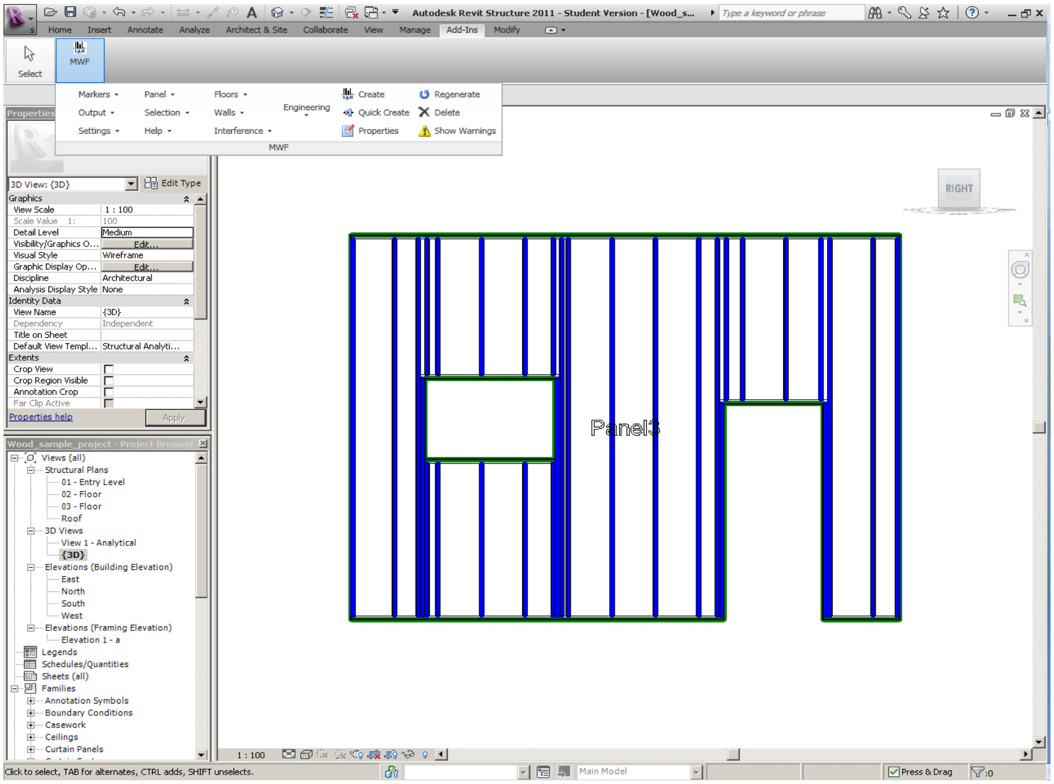

Figure 21. Generated frame in Autodesk Revit Structure with MWF plug-in

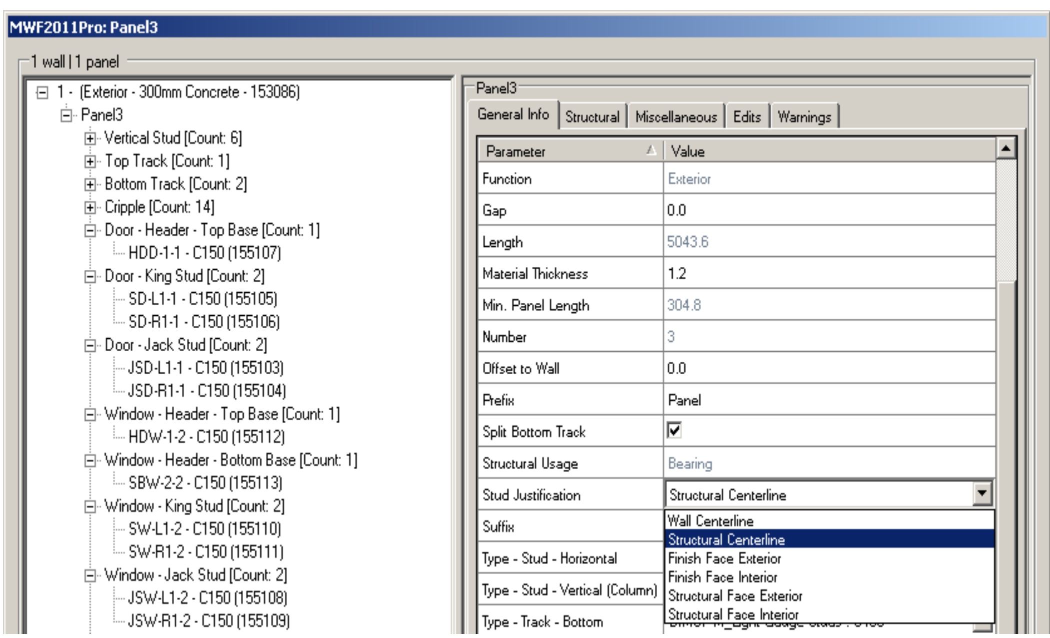

Figure 22. Frame in Revit Structure with MWF generating total number of studs

However, further research is needed to determine the exact number of contact points based on the geometry of each frame and for automatically getting the number of pre-cut studs from the geometry of the frame.

Real (on the jobsite) productivity data will need to be compared to the theoretical values used, but it is possible to use the scenario of the full-day activity for one crew. The exact sequencing of the framing activity can be obtained by using the two flowcharts presented earlier.

7.3 Conclusions for Crew Sizing Determination and Implementation in BIM

To recapitulate, in the previous chapters, the activities performed when building four different frames were video recorded and extensively analyzed. A formalization of the activities allowed for most of the precedence rules to be generated semi-automatically, using elementary formulas in Microsoft Excel (described in the methodology chapter). Corrections were made manually to accommodate for exceptions. This study validated the idea that full automation of micro-scheduling is possible and applicable to other construction trades.

The goals of the spin-off research presented in this chapter and the conclusions are reiterated below:

1. Since BIM can represent each component of each element (in this case studs and plates for light wood frames), it is possible to assign a series of tasks to the production and assembling of each component. Most of the geometrical constraints can be determined using simple geometrical reasoning. Microsoft Excel was successfully used to create the list of all the tasks and their precedents. However, the automation of the decisions

regarding subassemblies needs further research and is later discussed in the last chapter.

2. Late Start was consistently found to be the most effective criteria for micro-scheduling. However, the results can be used only as a theoretical base for decision-making as the sequence of operations on the critical path appears haphazard to the framers. The developed five-rule flowchart indicates that a certain task sequencing based on simpler, more natural criteria, provides similar efficiencies to the Late Start resource leveling criteria. The five-rule flowchart provides a good basis for determination beforehand of a crew or team sizing and the possibility to use selectively the crew performance for the purpose of assigning the actual labor to framing panels in existing BIM tools (not yet developed).

3. Calculating the maximum size of the teams without going through the entire process of P6 optimization is possible. Experienced foremen are most likely using a similar approach in a natural way, albeit subconsciously. They assign smaller teams (one or two framers) to simpler frames (i.e. fewer components and, hence, fewer tasks) and teams of three framers to build more complex frames. The minimum number of tasks for a team of three framers was determined to be around 200.

4. With relatively simple programming, BIM information can be used for team and crew sizing. The size of the teams can be determined based on the geometrical description of the frames. An approach similar to the one presented in this chapter is probably suitable for crew sizing as well.

However, the aggregation of the teams into crews allocated for various frames with different degrees of complexity needs further research.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

As stated in section 1.6, the purpose of this research was to answer the following two questions:

1. How do teams or crews solve problems together? In other words, how do they become aware of a particular situation as a group, how do they share information/situations and make decisions as a unit?
2. What role does individual performance play in the performance of the whole crew?

The subsequent sections answer these questions in an explicit manner, explain the limitations of the research and then provide recommendations for further research.

8.1 How Wood-Framing Teams or Crews Solve Problems Together

During normal framing operations, the decision of who performs what task on which element and when (i.e. the micro-scheduling of the team's activity), is done in a distributed manner (i.e. each framer is participating in the process without conscientiously coordinating with the other team members). This behavior can be obtained if each framer adheres to a set of five rules. Those five rules, in the order of their ranking, are as follows:

1. Complicated Elements
2. Safety
3. Similar Elements
4. Minimal walk
5. Stay with the Element

These rules have been tested against the results of best case scenario provided by Primavera P6 and were found to be necessary and sufficient. The maximum deviation between the five rules and P6 case was found to be 4.7 %.

While the framers may or may not be able to articulate these rules, their actions indicate that they mostly abide by them. The framers working on each of the four frames studied and analyzed as part of this research were successfully able to flow through the defined rules and flowcharts. This is validated by the following findings:

- The total production time obtained using the five-rule framework model is congruent with the minimum possible duration obtained using scheduling software (P6, using late-start leveling).
- The five-rule framework model helps create a sequence of tasks that is simple, realistic and easy to implement on site.

The five-rule framework can be converted into an algorithm that can be used for micro-scheduling (sequencing) to improve productivity and coordination of the entire crew.

The congruence of the five-rule framework model with the calculated minimum possible execution times, and the fact that in each case-study the framers followed these rules with relatively few faults, indicates that the problem solving capability of the crew is embedded in the capacity of each individual to understand and act upon the five-rule framework model.

8.2 The Role of Individual Performances in Team Coordination and Performance

The answer to the second research question "What role does individual performance play in the performance of the whole crew?" is that the team members should comply as much as possible with the five-rule model in order to achieve greater performance. In other words, for each team member, the procedural deviations from following the model are desired to be at the minimum levels. The average procedural deviation plays some role on the total productivity of the team ($R^2 = 0.8529$), but a more significant role is played by the procedural deviations of the worst framer (PDWF). This research has not encountered a case study with less than 12% PDWF; therefore this fact should be further investigated by undertaking additional studies. However, it can be inferred that any extra percent of PDWF above 11% (see Table 18) affects productivity of the entire team by a factor of 4. For instance, an increase of PDWF from 11% to 14% will decrease the productivity of the respective team by 12%.

This conclusion gives legitimacy to the practice of replacing <u>only</u> the worst performer in the team; it also provides a means for improving the productivity of the whole team by training the crew on the five rules. While it appears to be sufficient to train only the worst performer on the five rules, it makes more sense to train the whole team, thus eliminating the errors of the next to worst framer at the same time.

It is worth noting that the framer with the most procedural errors is not always the "expert" framer, nor is it the "novice". More research is needed to determine how swapping team members in a crew affect the performance of each team.

Sharing information/situations and making decisions as a unit (team) is reflected in the mental model of each individual framer and his/her capability to withstand ignoring rules from the framework. Based on the actual video observations and follow-up discussions with the foremen, it is concluded that in each case scenario the framers were not aware of following a “code” of procedures concisely (a certain task sequence). Matching the amount of time spent to synchronize the coordination levels between the framers can lead the team to make decisions as a unit for the benefit of the final product (the frame). Also, it is worth noting that in real life any and all five rules can be ignored in the flowcharts at any time by the framers. Potential reasons that the framers sometimes ignore the rules, even when constraints are released, have not been identified through this study and are in need of additional research. It is acknowledged in this research that there is a distinction between an ignored rule in the flowchart and an ignored task.

Each case study set-up was revealed a network of particular tasks and procedures to be followed by the team; the difficult question was how to compare the results of different teams knowing that each of them is following a different instance of the decision network. The answer, provided in the data analysis chapter, was to compare the total execution time with the time obtained through an optimum flowchart regulated by an effective “internal” mental model of individual framers. The role that individual performance plays in group performance and coordination rests with the degree of the mental model accuracy in the mind of the framer, the task procedure to be executed and a well understood distribution of the work between the crew members. These considerations are essential to coordination between individuals. The interaction between the crew members in this trade is essential for the decisive moments when redistribution of the tasks occurs and is necessary. This is based on one's awareness of others' work. Moreover, the individual roles in each crew are specific to the trade analyzed (in this research, wood-framing) because of the specificity of the framers' actions in their interactions with tools, equipment and materials.

Through the optimization process followed in the development of the flowchart, the roles of the individual are considered only in the critical decisive moments, when the framer is switching the performance of the inner flowchart tasks in opposition to adding tasks from the main pool (in the outer flowchart). This characteristic establishes how one's coordination skills compete with the team task and the capacity of the framer's mind to achieve an accurate mental model of the frame.

8.3 Implications in Productivity of the Framing Operations

As stated in the methodology chapter, in certain situations rework time was added to the tasks performed and executed erroneously; the error durations subtracted from the actual execution task time interferes in the P6 resource leveling optimization. If the errors would have been treated separately as different tasks (reworked tasks) with their own duration, it is very probable they would lead to a dissimilar total duration as bottom line in the P6 optimization process.

Understanding the full-range of factors leading to errors improves the productivity of operations and causes elimination of the tasks that are categorized as rework.

Productivity of framing operations will potentially be increased by using BIM in the pre-planning of the micro-operations. At this stage the possibility to automatically calculate the optimal team size for a frame was proven. More research is needed for the optimization of the crew assignments and the parting of the frame in subassemblies.

8.4 Limitations of This Study and Recommendations for Further Research

This research study has some limitations that are listed below. Some of them were succinctly mentioned in the previous chapters.

- In the current study, a task, when not performed in its sequence, got carried as a backlog (in multiple rounds) until the framer returned and executed it. This provoked a question that needs further research: "How long can a framer carry his backlog (remember the task in his mind) of tasks to be performed?"
- This research did not take into account the impact of material and shape differences on framer's individual productivity; the time needed to perform a task on different material (lumber vs. particle board) did not present an explicit difference. Material may play an important role for other construction trades and should be considered during future research (different types of actions in the task description and numerical assignment).

- The case studies documented, analyzed and tested for the feasibility of the five-rule framework model are limited to wood-framing for now. Expanding the scope of this research by implementing this five-rule framework model on other construction trades will further validate its applicability in improving jobsite team productivity through coordination and will provide further possibilities for automation.

It is worth noting that the P6 optimization process was not really necessary for developing the compliance rate calculations for each individual framer. The optimization process approach was helpful though to establish the minimum possible time to perform the tasks on the respective frames and validation of the five-rule framework.

To obtain a high level of coordination and performance in larger framing teams future research will have to focus on how individual mental models merge into a unique top-performance team mental model. The following should be considered for studies involving larger teams:

- Flexibility – acknowledged by cost of mistakes, or procedural deviations of following the flowchart in relation to productivity, safety and quality of work.
- Accommodation – for skill variation of the work coordination within individual members of the team.
- Network capability - to accommodate perturbations, through metrics capable of correcting the errors during backlog work.

Further research is needed to determine the exact number of contact points based on the geometry of each given frame. As mentioned in the previous chapter, the possibility of getting the number of pre-cut studs from the geometry of the frame and the crew size may be addressed for further development of the step function.

The need for further research regarding automation of the decisions concerning subassemblies was exposed by this study. There is a certain influence on the productivity and quality of the frame when a lead framer is taking care of the subassemblies (usually headers for window and door openings, jack studs for doors, top and sole plates, etc.). This influence can be measured in quantitative terms and can be traced back to the cognitive abilities of the lead framer.

A framer's decision to execute a task varies based on site conditions (external to the work setting) and the complexity of that individual frame (internal to the work setting). However, this research did not focus on how these internal sequence violations are addressed in the team environment and team interaction, thus it is a potential for further research. It is concluded that the number of choices framers make in following the right work sequence (in their mental model) is not proportional to the complexity of the frame on which they are working.

There has not been enough research in planning the task sequencing (micro-scheduling), crew size and work distribution among various trades and their impact on crew productivity. The study presented here focuses mainly on improving productivity and coordination of the framing operations through a framework model that ranks five rules in the minds of the framers. The five-rule framework is a team level mental model developed to aid in designing the process flow at the micro level for wood framing walls in buildings. The data collected and analyzed from four different residential project sites was enough to substantiate the validation of the working model. The results of this research help the progress of confirming the possibility of full automation of micro-scheduling while improving productivity and coordination on the job-site. They also provide further research opportunity to prove its applicability among other trades' activities. However, the coordination dependency acknowledged in Figure 17 was drawn on the four data point basis (from all four case studies). In order to establish a stronger dependency relationship between PDWF and the Productivity Decline, additional data points may be considered (additional case studies).

As stated in section 1.4., the results of this research allow a broader integration of people in construction, regardless of gender or stature, through:

- Providing new capabilities for analysis of framing operations through an innovative methodology and analysis.
- Describing with accuracy the team mental model and procedures to the final outcome to achieve highly coordinated and high-performance teams.
- Fitting coordination skills with team task for structuring adaptive teams through an accurate team mental model.

Finally, it is concluded that following the flowchart as closely as possible means a better understanding of the mental model of the final product in the minds of the individuals, thus more chances to achieve better coordination and a high-performing crew. The common team plan deployed for achieving optimum performance consists of individuals with high rate of compliance and low average procedural deviations per team. In the selection of framing crews, this fact allows a superintendent or foreman to realize how well the team executes the common plan and to intervene with specific training or to match individual coordination skills between framers to achieve a high-performance team.

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APPENDIX A

QUALITY CHECK LISTS

A1. Quality check lists

The quality lists are provided for reference and pertain mainly to the framing of residential or commercial buildings.

Wall framing (quality checks): walls located per "approved" drawings; check walls for straightness, plumb, and square; correct size lumber for studs and headers; Check sheathing size, manufacturer's installation instructions, and nailing schedule per code; Check critical dimensions; no room studded without installing large fixtures or appliances that will not fit through door openings later; Check window and door openings; check dimensions, plumb, square (Note: Rough framing for window and door openings will require a thorough review with vendors to determine allowances for products chosen for installation - items such as floor covering, door and window trim will affect the allowances for framing measurements); Check all warped studs removed or straightened; pull string along wall lines to determine straightness; Check plate splices located over studs; Check trimmer studs and header joints tight; Check garage door jamb and brick mold installed properly; Check framing and drywall installation per fire code in areas surrounding fireplace masonry (coordination of this activity with framer and masonry contractors prior to enclosure); Check that walls have adequate temporary bracing to maintain straightness and plumb prior to setting truss package.

Roof framing (quality checks):

(Note: Roof framing may be "stick frame" or "truss package". The main difference is that "stick frame" roofs will be built piece by piece on site; a roof erected with a "truss package" will be cut and assembled at the factory and delivered to the site)

Check trusses erected according to engineered design and installation instructions accompanying package:

1. Nailing schedule per applicable building code
2. Framing anchors installed per applicable building code
3. Catwalk installed at center of attic
4. Wind brace installed at gable ends
5. Attic vents installed at gable ends or ridge
6. All gable and firewall trusses have studs installed per sheathing or drywall layout
7. Lookouts installed at peak of gable and 4' o.c. for sheathing layout
8. Fascia and Barge boards installed straight and secure
9. Vent blocks installed at exterior walls between roof rafters

Check stick framing installed per "approved" drawings according to applicable building code:

1. Rafters correct size, straight, crown-up
2. Ridge board correct size, straight, without sag
3. Rafters properly connected to wall plates
4. Collar ties correct size, spacing, height
5. Vent blocks installed at exterior walls between rafters
6. Attic vents installed at gable ends or ridge
7. Fascia and Barge boards installed straight and secure

8. Lookouts and rake supports installed per layout

Check for proper clearance around chimney; Check attic access properly sized and located; Check that ceiling backing is in place before sheathing is installed; Check location and backing for skylights.

APPENDIX B

PRODUCTIVITY AND DURATION COMPARISON CHARTS

Table B1. Duration and Productivity in P6 (Late Start priority rule) – Case Study Two

No.	Priority Rule	Total Duration	Resource units	No. of People	CPM	Equiv. Time	Prod. frame	Duration
1	Late Start	1012	100%	1	S-H 15-T 15-C 15-N 15 14-H 30-P 30-N 16 30-P 25-N 25 16-Lift	1012	103%	291%
		514	200%	2	Same	1028	102%	148%
		348	300%	3	Same	1044	100%	100%
		265	400%	4	Same	1060	98%	76%
		231	500%	5	Same	1155	90%	66%
		231	600%	6	Same	1386	75%	66%
		231	700%	7	Same	1617	65%	66%

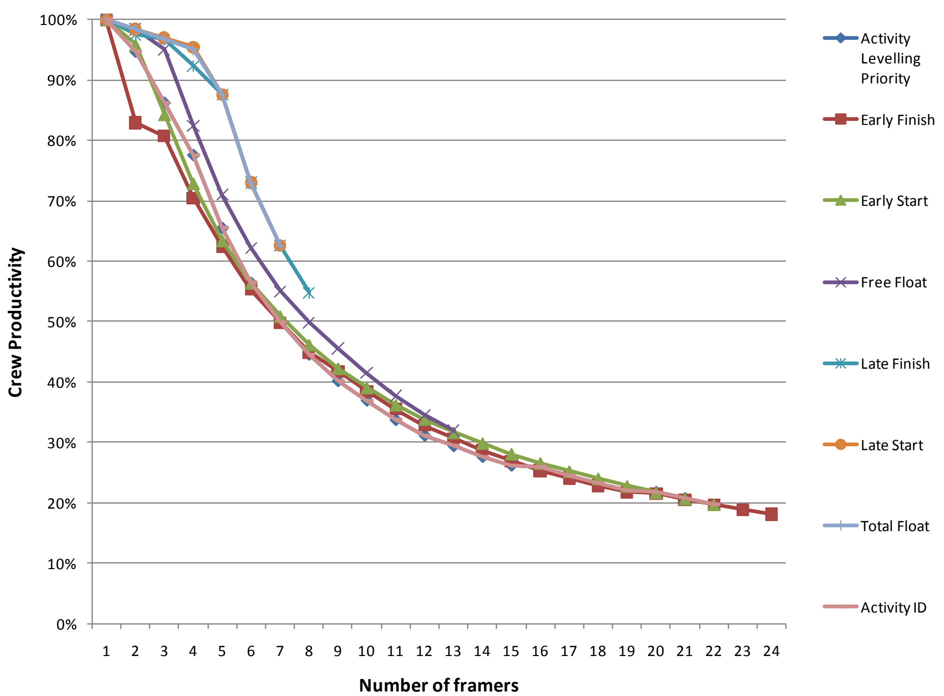

Figure B1. Productivity comparison for different leveling priority rules in P6 – case study two

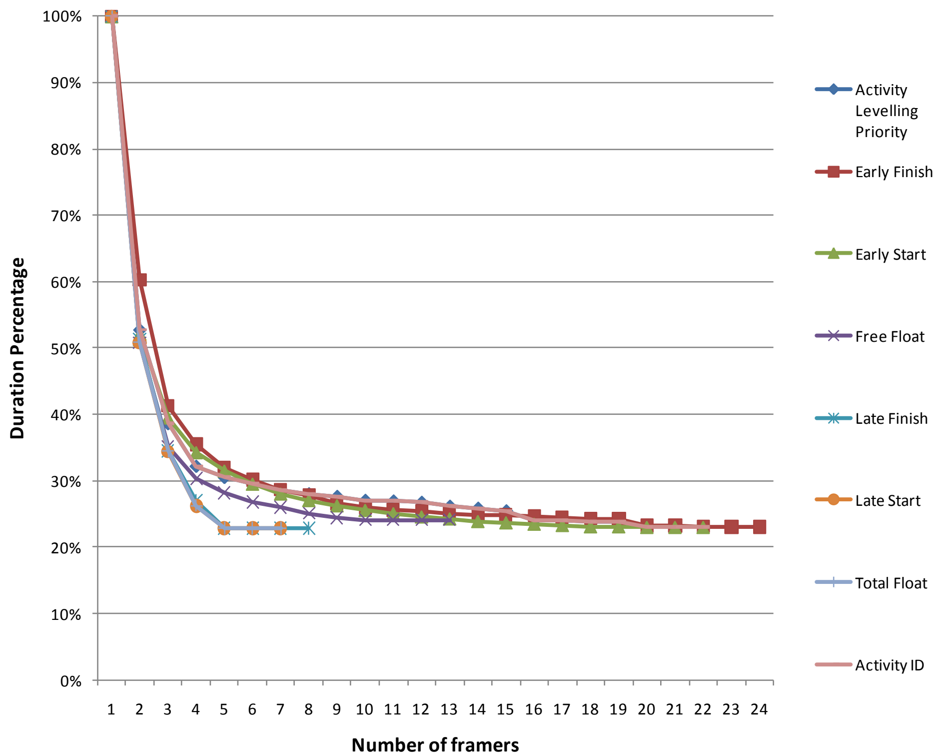

Figure B2. Duration comparison for different leveling priority rules in P6 – case study two

Table B2. Duration and Productivity in P6 (Late Start Priority Rule) – Case Study Three

No.	Priority Rule	Total Duration	Resource units	No. of People	CPM	Equiv. Time	Prod. frame	Duration
1	LS	789	100%	1	S-H 34-T 34-C 34-N 32 34 33-P 40-N 38 40-P 36-N 02 36-P 37-N 37 02-Lift	789	100%	100%
		399	200%	2	same	798	99%	51%
		269	300%	3	same	807	98%	34%
		204	400%	4	same	816	97%	26%
		169	500%	5	same	845	93%	21%
		169	600%	6	same	1014	78%	21%

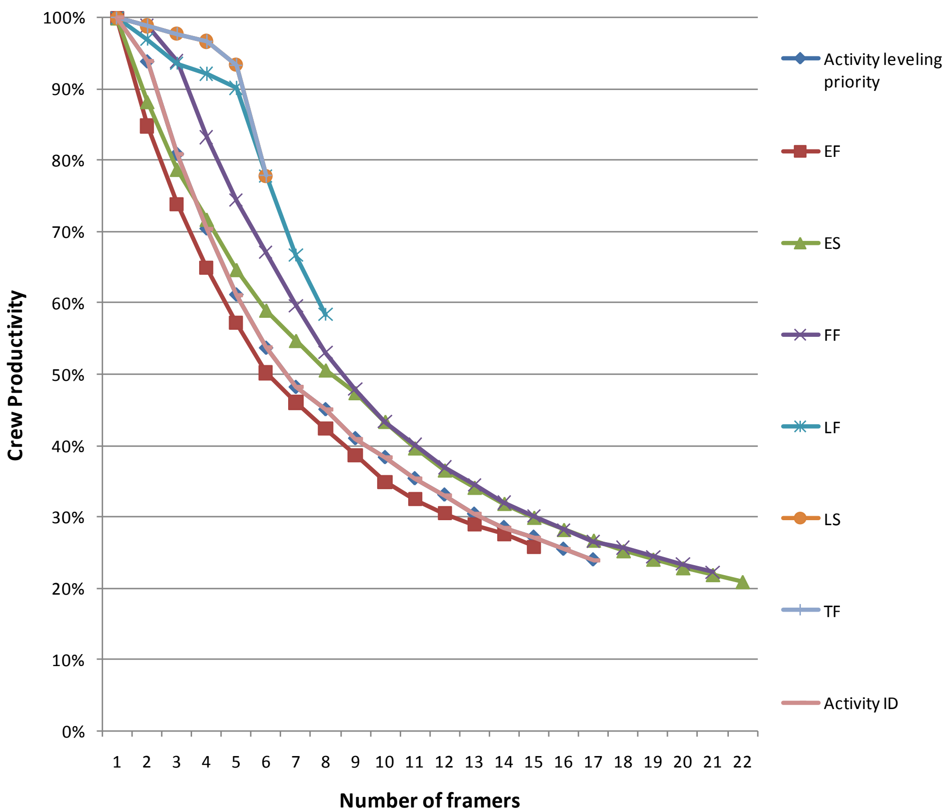

Figure B3. Productivity comparison for different leveling priority rules in P6 – case study three

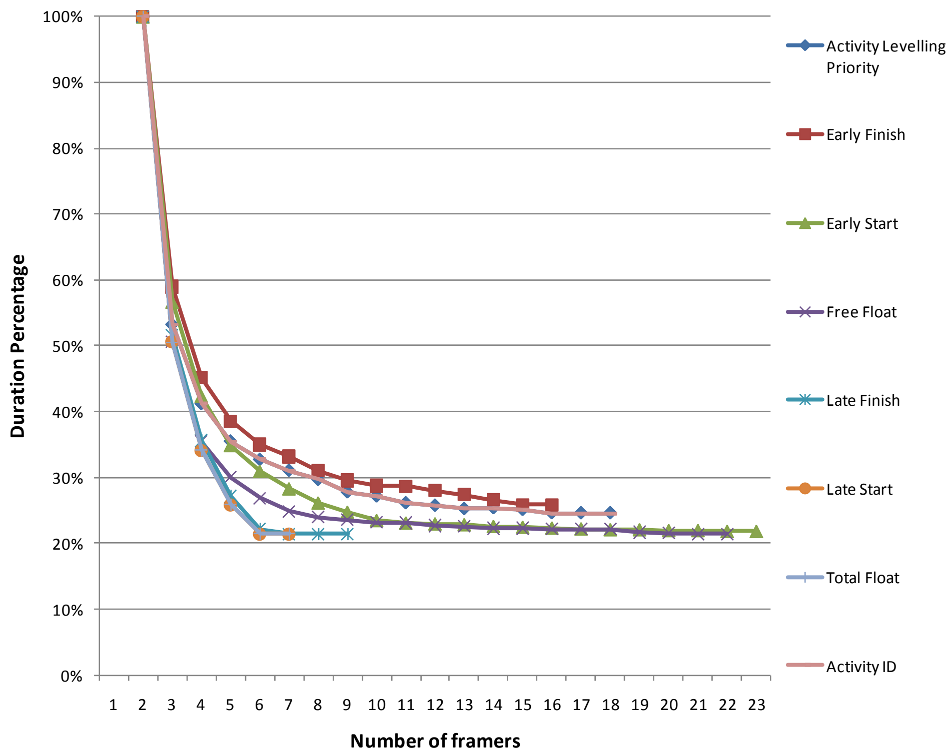

Figure B4. Duration comparison for different leveling priority rules in P6 – case study three

Table B3. Duration and Productivity in P6 (Late Start Priority Rule) – Case Study Four

No.	Priority Rule	Total Duration	Resource units	No. of People	CPM	Equiv. Time	Prod. Frame	Duration
1	Late Start	923	100%	1	S, H 17, T 17, C 17, N 17 18, H 60, P 60, N 65 60, P 46, N 03 46, P 49, N 49 03, Lift	923	100%	100%
		466	200%	2	same	932	99%	50%
		314	300%	3	same	942	98%	34%
		238	400%	4	same	952	97%	26%
		192	500%	5	same	960	96%	21%
		162	600%	6	same	972	95%	18%
		140	700%	7	same	980	94%	15%
		124	800%	8	same	992	93%	13%
		111	900%	9	same	999	92%	12%
		101	1000%	10	same	1010	91%	11%
		93	1100%	11	same	1023	90%	10%
		86	1200%	12	same	1032	89%	9%
		80	1300%	13	same	1040	89%	9%
		75	1400%	14	same	1050	88%	8%
		73	1500%	15	same	1095	84%	8%
		73	1600%	16	same	1168	79%	8%

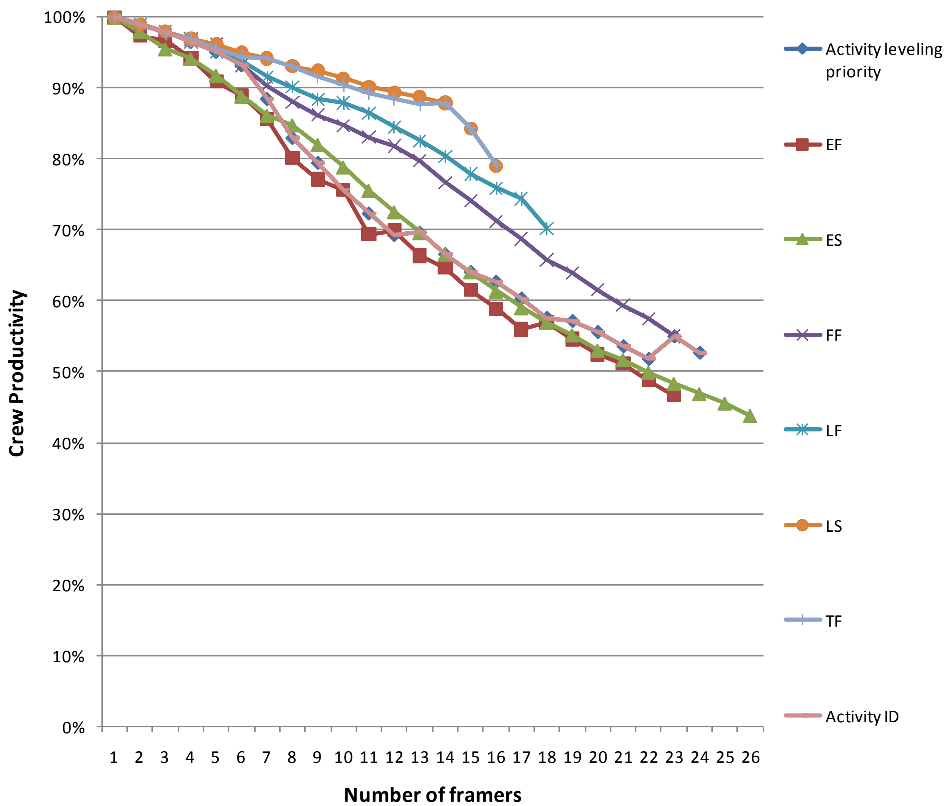

Figure B5. Productivity comparison for different leveling priority rules in P6 – case study four

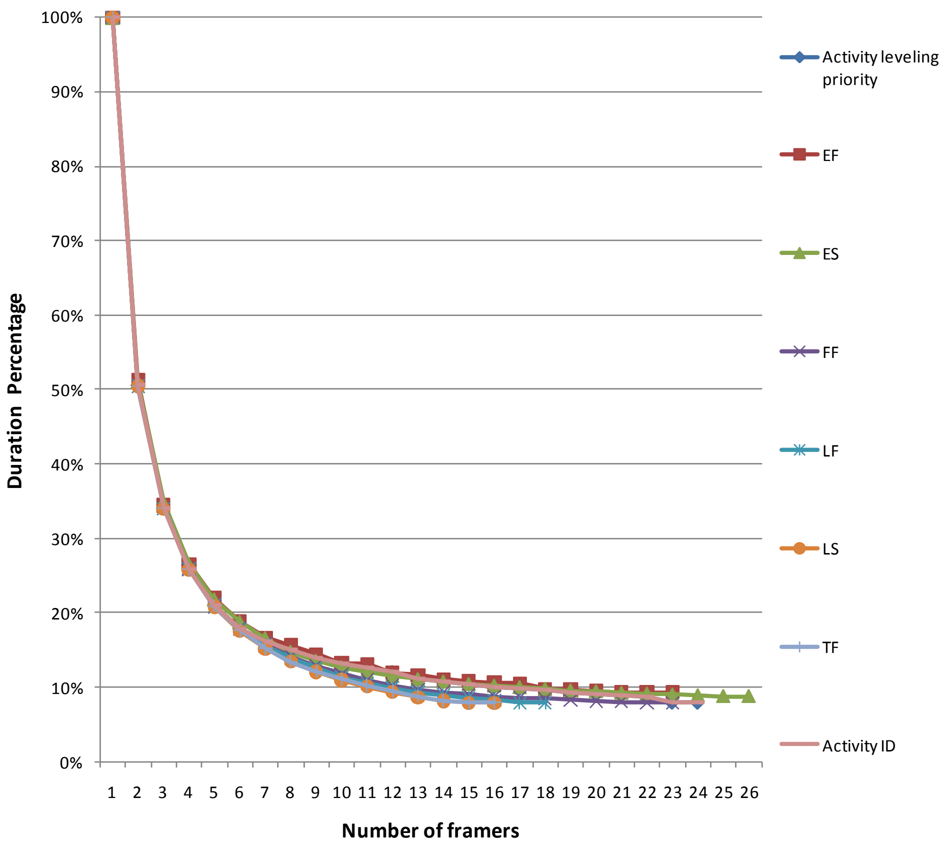

Figure B6. Duration comparison for different leveling priority rules in P6 – case study four

APPENDIX C

FLOWCHART VALIDATION FOR FRAME TWO

FRAME TWO: INNER FLOWCHART

Table C1. Frame Two, Framer 1: Mental Stack in Round 1

^H 16^	^H 16^	H 16	#P 16#	#P 16#	#P 16#	#P 16#
^H 02^	H 02	#P 16#	^P 02^	^P 02^	P 02	^N 01 02^
H 01	*P 16*	^P 02^	^P 01^	P 01	^N 01 02^	*M 16 23*
P 16	^P 02^	^P 01^	*N 01 02*	*N 01 02*	*M 16 23*	*M 16 24*
P 02	^P 01^	*N 01 02*	M 33 03	*M 16 23*	*M 16 24*	
^P 01^	*N 01 02*	^M 33 03^	M 16 03	*M 16 24*		
N 01 02	*M 33 03*	^M 16 03^	M 33 04			
M 33 03	*M 16 03*	^M 33 04^	M 16 04			
M 16 03	*M 33 04*	^M 16 04^	M 33 06			
M 33 04	*M 16 04*	^M 33 06^	M 16 06			
M 16 04	*M 33 06*	^M 16 06^	M 33 07			
M 33 06	*M 16 06*	^M 33 07^	M 16 07			
M 16 06	*M 33 07*	^M 16 07^	*M 16 23*			
M 33 07	*M 16 07*	M 33 05	*M 16 24*			
M 16 07	*M 33 05*	M 16 05				
M 33 05	*M 16 05*	M 33 08				
M 16 05	*M 33 08*	M 16 08				
M 33 08	*M 16 08*	M 33 09				
M 16 08	*M 33 09*	M 16 09				
M 33 09	*M 16 09*	M 33 10				
M 16 09	*M 33 10*	M 16 10				
M 33 10	*M 16 10*	M 33 11				
M 16 10	*M 33 11*	M 16 11				
M 33 11	*M 16 11*	M 33 12				
M 16 11	*M 33 12*	M 16 12				
M 33 12	*M 16 12*	M 33 13				
M 16 12	*M 33 13*	M 16 13				
M 33 13	*M 16 13*	M 33 22				
M 16 13	*M 33 22*	M 16 22				
M 33 22	*M 16 22*	M 33 14				
M 16 22	*M 33 14*	M 16 14				
M 33 14	*M 16 14*	*M 16 24*				
M 16 14	*M 16 24*	*M 16 23*				
M 16 24	*M 16 23*					
M 16 23						

LEGEND

$\_\_\_$ Is not min. walk
___ Predecessor not complete
^___^ Is a Violation
~___~ Is a Task from other framer's pool
#___# Is not safe
[shaded] Executed task

Table C2. Frame Two, Framer 1: Mental Stack in Round 2 (continued)

#P 16#	#P 16#	#P 16#	#P 16#	#P 16#	#P 16#	#P 16#	#P 16#
^N 01 02^	^N 01 02^	^N 01 02^	^N 01 02^	^N 01 02^	^N 01 02^	^N 01 02^	^N 01 02^
M 16 23	*M 16 23*	*M 16 23*	*M 16 23*	*M 16 23*	*M 16 23*	*M 16 23*	*M 16 23*
M 16 24	*M 16 24*	*M 16 24*	*M 16 24*	*M 16 24*	*M 16 24*	*M 16 24*	*M 16 24*
=======	======	=======	========	========	========	========	=======
H 03	H 04	^H 06^	H 06	H 07	^H 08^	^H 08^	^H 08^
$H 04$	$H 06$	^H 07^	^H 07^	$H 08$	^H 09^	^H 09^	^H 09^
$H 06$	$H 07$	H 05	$H 08$	$H 09$	^H 10^	^H 10^	^H 10^
$H 07$	$H 05$	$H 08$	$H 09$	$H 10$	^T 08 ^	^T 08 ^	^T 08 ^
$H 05$	$H 08$	$H 09$	$H 10$	$T 08$	^T 09^	^T 09^	^T 09^
$H 08$	$H 09$	$H 10$	$T 08$	$T 09$	^T 10^	^ T 10^	^T 10^
$H 09$	$H 10$	$T 08$	$T 09$	$T 10$	$H 11$	H 11	H 12
$H 10$	$T 08$	$T 09$	$T 10$	$H 11$	$H 12$	$H 12$	$H 13$
$T 08$	$T 09$	$T 10$	$H 11$	$H 12$	$H 13$	$H 13$	$H 22$
$T 09$	$T 10$	$H 11$	$H 12$	$H 13$	$H 22$	$H 22$	$H 21$
$T 10$	$H 11$	$H 12$	$H 13$	$H 22$	$H 21$	$H 21$	^P 08^
$H 11$	$H 12$	$H 13$	$H 22$	$H 21$	^P 08^	^P 08^	P 12
$H 12$	$H 13$	$H 22$	$H 21$	P 07	P 09	P 11	*P 13*
$H 13$	$H 22$	$H 21$	P 06	*P 08*	P 10	*P 12*	*P 22*
$H 22$	$H 21$	*P 06*	*P 07*	*P 09*	*P 11*	*P 13*	*P 21*
$H 21$	P 04	*P 07*	*P 08*	*P 10*	*P 12*	*P 22*	^N 33 03^
P 03	*P 06*	P 05	*P 09*	*P 11*	*P 13*	*P 21*	*N 16 03*
P 04	*P 07*	*P 08*	*P 10*	*P 12*	*P 22*	^N 33 03^	^N 33 04^
P 06	*P 05*	*P 09*	*P 11*	*P 13*	*P 21*	*N 16 03*	*N 16 04*
P 07	*P 08*	*P 10*	*P 12*	*P 22*	^N 33 03^	^N 33 04^	^N 33 06^
P 05	*P 09*	*P 11*	*P 13*	*P 21*	*N 16 03*	*N 16 04*	*N 16 06*
P 08	*P 10*	*P 12*	*P 22*	^N 33 03^	^N 33 04^	^N 33 06^	^N 33 07^
P 09	*P 11*	*P 13*	*P 21*	*N 16 03*	*N 16 04*	*N 16 06*	*N 16 07*
P 10	*P 12*	*P 22*	^N 33 03^	^N 33 04^	^N 33 06^	^N 33 07^	^N 33 05^
P 11	*P 13*	*P 21*	*N 16 03*	*N 16 04*	*N 16 06*	*N 16 07*	*N 16 05*
P 12	*P 22*	^N 33 03^	^N 33 04^	^N 33 06^	^N 33 07^	^N 33 05^	*N 33 08*
P 13	*P 21*	*N 16 03*	*N 16 04*	*N 16 06*	*N 16 07*	*N 16 05*	*N 16 08*
P 22	^N 33 03^	^N 33 04^	^N 33 06^	^N 33 07^	^N 33 05^	*N 33 08*	^N 33 09^
P 21	*N 16 03*	*N 16 04*	*N 16 06*	*N 16 07*	*N 16 05*	*N 16 08*	*N 16 09*
^N 33 03^	^N 33 04^	*N 33 06*	*N 33 07*	^N 33 05^	*N 33 08*	^N 33 09^	^N 33 10^
N 16 03	*N 16 04*	*N 16 06*	*N 16 07*	*N 16 05*	*N 16 08*	*N 16 09*	*N 16 10*
N 33 04	*N 33 06*	*N 33 07*	^N 33 05^	*N 33 08*	^N 33 09^	^N 33 10^	^N 33 11^
N 16 04	*N 16 06*	*N 16 07*	*N 16 05*	*N 16 08*	*N 16 09*	*N 16 10*	*N 16 11*
N 33 06	*N 33 07*	^N 33 05^	*N 33 08*	*N 33 09*	^N 33 10^	^N 33 11^	*N 33 12*
N 16 06	*N 16 07*	*N 16 05*	*N 16 08*	*N 16 09*	*N 16 10*	*N 16 11*	*N 16 12*
N 33 07	*N 33 05*	*N 33 08*	*N 33 09*	*N 33 10*	*N 33 11*	*N 33 12*	*N 33 13*
N 16 07	*N 16 05*	*N 16 08*	*N 16 09*	*N 16 10*	*N 16 11*	*N 16 12*	*N 16 13*
N 33 05	*N 33 08*	*N 33 09*	*N 33 10*	*N 33 11*	*N 33 12*	*N 33 13*	*N 33 22*
N 16 05	*N 16 08*	*N 16 09*	*N 16 10*	*N 16 11*	*N 16 12*	*N 16 13*	*N 16 22*
N 33 08	*N 33 09*	*N 33 10*	*N 33 11*	*N 33 12*	*N 33 13*	*N 33 22*	*N 33 21*
N 16 08	*N 16 09*	*N 16 10*	*N 16 11*	*N 16 12*	*N 16 13*	*N 16 22*	*N 16 21*
N 33 09	*N 33 10*	*N 33 11*	*N 33 12*	*N 33 13*	*N 33 22*	*N 33 21*	
N 16 09	*N 16 10*	*N 16 11*	*N 16 12*	*N 16 13*	*N 16 22*	*N 16 21*	
N 33 10	*N 33 11*	*N 33 12*	*N 33 13*	*N 33 22*	*N 33 21*		
N 16 10	*N 16 11*	*N 16 12*	*N 16 13*	*N 16 22*	*N 16 21*		
N 33 11	*N 33 12*	*N 33 13*	*N 33 22*	*N 33 21*			
N 16 11	*N 16 12*	*N 16 13*	*N 16 22*	*N 16 21*			
N 33 12	*N 33 13*	*N 33 22*	*N 33 21*				
N 16 12	*N 16 13*	*N 16 22*	*N 16 21*				
N 33 13	*N 33 22*	*N 33 21*					
N 16 13	*N 16 22*	*N 16 21*					
N 33 22	*N 33 21*						
N 16 22	*N 16 21*						
N 33 21							
N 16 21							

Table C2. Frame Two, Framer 1: Mental Stack in Round 2 (continued)

#P 16#	#P 16#	#P 16#	P 16	*M 16 23*	*M 16 23*	*M 16 23*	*M 16 23*
^N 01 02^	N 01 02	*M 16 23*	*M 16 23*	*M 16 24*	*M 16 24*	*M 16 24*	*M 16 24*
M 16 23	*M 16 23*	*M 16 24*	*M 16 24*	========	=======	=======	=======
M 16 24	*M 16 24*	======	=======	^H 08^	^H 08^	^H 08^	^H 08^
^H 08^	^H 08^	^H 08^	^H 08^	^H 09^	^H 09^	^H 09^	^H 09^
^H 09^	^H 09^	^H 09^	^H 09^	^H 10^	^H 10^	^H 10^	^H 10^
^H 10^	^H 10^	^H 10^	^H 10^	^T 08 ^	^T 08 ^	^T 08 ^	^T 08 ^
^T 08 ^	^T 08 ^	^T 08 ^	^T 08 ^	^T 09^	^T 09^	^T 09^	^T 09^
^T 09^	^T 09^	^T 09^	^T 09^	^T 10^	^T 10^	^T 10^	^T 10^
^T 10^	^T 10^	^T 10^	^T 10^	$H 22$	$H 22$	$H 22$	$H 22$
H 13	$H 22$	$H 22$	$H 22$	$H 21$	$H 21$	$H 21$	$H 21$
$H 22$	$H 21$	$H 21$	$H 21$	^P 08^	^P 08^	^P 08^	^P 08^
$H 21$	^P 08^	^P 08^	^P 08^	*P 22*	*P 22*	*P 22*	*P 22*
^P 08^	*P 22*	*P 22*	*P 22*	*P 21*	*P 21*	*P 21*	*P 21*
P 13	*P 21*	*P 21*	*P 21*	^N 16 04^	^N 16 04^	^N 16 04^	^N 16 04^
P 22	*N 16 03*	*N 16 03*	N 16 03	^N 16 06^	^N 16 06^	^N 16 06^	^N 16 06^
P 21	*N 16 04*	*N 16 04*	^N 16 04^	^N 16 07^	^N 16 07^	^N 16 07^	^N 16 07^
N 33 03	*N 16 06*	*N 16 06*	^N 16 06^	^N 16 05^	^N 16 05^	^N 16 05^	^N 16 05^
N 16 03	^N 33 07^	N 33 07	^N 16 07^	^N 16 08^	^N 16 08^	^N 16 08^	^N 16 08^
N 33 04	*N 16 07*	*N 16 07*	^N 16 05^	^N 16 09^	^N 16 09^	^N 16 09^	N 16 09
N 16 04	N 33 05	*N 16 05*	^N 16 08^	^N 16 10^	^N 16 10^	N 16 10	*N 33 22*
N 33 06	*N 16 05*	N 33 08	^N 16 09^	^N 16 11^	N 16 11	*N 33 22*	*N 16 22*
N 16 06	*N 33 08*	*N 16 08*	^N 16 10^	N 16 12	*N 33 22*	*N 16 22*	*N 33 21*
^N 33 07^	*N 16 08*	N 33 09	^N 16 11^	*N 33 22*	*N 16 22*	*N 33 21*	*N 16 21*
N 16 07	^N 33 09^	*N 16 09*	^N 16 12^	*N 16 22*	*N 33 21*	*N 16 21*	
^N 33 05^	*N 16 09*	N 33 10	N 16 13	*N 33 21*	*N 16 21*		
N 16 05	^N 33 10^	*N 16 10*	*N 33 22*	*N 16 21*			
N 33 08	*N 16 10*	N 33 11	*N 16 22*				
N 16 08	^N 33 11^	*N 16 11*	*N 33 21*				
^N 33 09^	*N 16 11*	N 33 12	*N 16 21*				
N 16 09	*N 33 12*	*N 16 12*					
^N 33 10^	*N 16 12*	N 33 13					
N 16 10	*N 33 13*	*N 16 13*					
^N 33 11^	*N 16 13*	*N 33 22*					
N 16 11	*N 33 22*	*N 16 22*					
N 33 12	*N 16 22*	*N 33 21*					
N 16 12	*N 33 21*	*N 16 21*					
N 33 13	*N 16 21*						
N 16 13							
N 33 22							
N 16 22							
N 33 21							
N 16 21							

Table C2. Frame Two, Framer 1: Mental Stack in Round 2 (continued)

M 16 23 *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ $H 22$ $H 21$ ^P 08^ *P 22* *P 21* ^N 16 04^ ^N 16 06^ ^N 16 07^ ^N 16 05^ N 16 08 *N 33 22* *N 16 22* *N 33 21* *N 16 21*	*M 16 23* *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ $H 22$ $H 21$ ^P 08^ *P 22* *P 21* ^N 16 04^ ^N 16 06^ ^N 16 07^ N 16 05 *N 33 22* *N 16 22* *N 33 21* *N 16 21*	*M 16 23* *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ $H 22$ $H 21$ ^P 08^ *P 22* *P 21* ^N 16 04^ ^N 16 06^ N 16 07 *N 33 22* *N 16 22* *N 33 21* *N 16 21*	*M 16 23* *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ $H 22$ $H 21$ ^P 08^ *P 22* *P 21* ^N 16 04^ N 16 06 *N 33 22* *N 16 22* *N 33 21* *N 16 21*	*M 16 23* *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ $H 22$ $H 21$ ^P 08^ *P 22* *P 21* N 16 04 *N 33 22* *N 16 22* *N 33 21* *N 16 21*	*M 16 23* *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ $H 22$ H 21 ^P 08^ *P 22* P 21 *N 33 22* *N 16 22* N 33 21 N 16 21	*M 16 23* *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ H 22 ^P 08^ P 22 *N 33 22* N 16 22	*M 16 23* *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ ^P 08^ N 33 22	*M 16 23* *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ ^P 08^

Table C3. Frame Two, Framer 1: Mental Stack in Round 3

M 16 23 *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ ^P 08^ N 33 22 ~N 33 30~ ~N 16 30~ H 25 T 25 C 25 P 25 ^N 25 16^	*M 16 23* *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ ^P 08^ ======= ^N 25 16^

Table C4. Frame Two, Framer 1: Mental Stack in Round 4

M 16 23 *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ ^P 08^ N 33 22 ^N 25 16^ ======== H 27 T 27 C 27 P 27 N 27 16	*M 16 23* *M 16 24* ======== ^H 08^ ^H 09^ ^H 10^ ^T 08 ^ ^T 09^ ^T 10^ ^P 08^ ======= ^N 25 16^ =======

Table C5. Frame Two, Framer 2: Mental Stack in Round 1

H 17 ^H 18^ H 32 I 32 C 32 *N 17 32 18* *H 29* *P 29*	H 18 N 17 32 18 H 29 *P 29*	*P 29*

Table C6. Frame Two, Framer 2: Mental Stack in Round 2

P 29 ======== ~H 08~ ~H 09~ ~H 10~ ~T 08~ ~T 09~ ~T 10~ ~P 08~ H 15 $H 19$ T 15 *T 19* ^C 15^ *C 19* *H 14* *H 20* *N 15 14* *N 19 20* *H 30* *P 30* *P 31* *N 30 29* *N 31 29* *N 33 30* *N 28 31* *N 16 30* *N 16 31*	*P 29* ======== H 19 T 19 C 15 C 19 H 14 $H 20$ N 15 14 *N 19 20* H 30 P 30 *P 31* *N 30 29* *N 31 29* ^N 33 30^ *N 28 31* *N 16 30* *N 16 31*	*P 29* ======= H 20 N 19 20 P 31 *N 30 29* *N 31 29* ^N 33 30^ *N 28 31* *N 16 30* *N 16 31*	P 29 ======== N 30 29 N 31 29 ^N 33 30^ *N 28 31* *N 16 30* N 16 31	========= ^N 33 30^ *N 28 31* *N 16 30*

Table C7. Frame Two, Framer 2: Mental Stack in Round 3

======== ^N 33 30^ *N 28 31* *N 16 30* ======== H 28 T 28 C 28 ^P 28^	======== ^N 33 30^ *N 28 31* *N 16 30* ======= ^P 28^

Table C8. Frame Two, Framer 2: Mental Stack in Round 4

======== ^N 33 30^ *N 28 31* *N 16 30* ======== ^P 28^ ======== H 23 H 24 T 23 T 24 C 23 C 24 ~M 16 23~ ~M 16 24~ P 23 $P 24$ N 16 23 *N 16 24* *N 29 24* ^N 23 29^	======== ^N 33 30^ *N 28 31* *N 16 30* ======== ^P 28^ ======== P 24 N 16 24 N 29 24 N 23 29	======== ^N 33 30^ *N 28 31* *N 16 30* ======== ^P 28^ ========

Table C9. Frame Two, Framer 2: Mental Stack in Round 4

======== ^N 33 30^ *N 28 31* *N 16 30* ======== ^P 28^ ======== ======== H 26 P 26 N 26 31 *N 28 26* ~N 25 16~	======== ^N 33 30^ *N 28 31* *N 16 30* ======== P 28 ======== ======== N 28 26 ~N 25 16~	======== ^N 33 30^ N 28 31 *N 16 30* ======== ======== ======== ~N 25 16~	======== ^N 33 30^ *N 16 30* ======== ======== ========

Table C10. List of Actual Task Execution Sequence for Frame 2 (c'ed next page)

Expert -Framer 1 (red shirt)		Novice - Framer 2 (gray shirt)	
Task ID	**Duration (sec.)**	**Task ID**	**Duration (sec.)**
H 1	1	H 17	1
H 2	2	H 32	1
H 16	13	I 32	5
M 02 05	1	C 32	14
M 16 05	1	H 18	8
M 02 08	1	N 17_32_18	14
M 16 08	1	H 29	5
M 02 09	1	N 01 03	3
M 16 09	1	N 01 04	4
M 02 10	10	H 08	7
M 16_10	1	H 09	7
M 02_11	1	H 10	5
M 16_11	1	T 08	3
M 02_12	2	T 09	2
M 16_12	1	T 10	2
M 02_13	11	P 08	6
M 16_13	1	P 09	8
M 02_22	1	N 01 06	4
M 16_22	1	N 01 02	3
M 02_14	2	H 15	1
M 16_14	5	T 15	14
M 01_03	1	H 19	1
M 16_03	1	T 19	17
M 01_04	1	C 15	11
M 16_04	1	C 19	9
M 01_06	2	H 14	1
M 16_06	1	N 15_14	117
M 02_07	5	H 30	10
M 16_07	1	P 30	2
P 01	2	H 20	1
P 02	11	N 19_20	66
H 03	3	P 31	3
P 03	3	P 29	11
H 04	3	H 28	6
P 04	2	T 28	5
H 05	7	C 28	2
P 05	2	H 23	1
N 02 05	10	H 24	1
H 06	4	T 23	5
P 06	2	T 24	4
H 07	6	C 23	3
P 07	2	C 24	4
P 10	1	M 16_23	11
H 11	2	M 16_24	5
P 11	1	P 23	9
H 12	3	N 16_23	2
P 12	1	P 24	12
H 13	6	N 16_24	2
P 13	2	N 29_24	2
N 02 07	17	N 23_29	3
N 02_08	8	P 25	22
N 02_09	11	N 25_16	19
N 02_10	10	H 26	2

Expert -Framer 1 (red shirt)		**Novice - Framer 2 (gray shirt)**	
N 02_11	10	P 26	2
N 02_12	7	N 26_31	18
N 02_13	11	P 28	6
P 16	9	N 28 _26	1
N 16 03	1	N 28 31	3
N 16 13	4	*LIFT*	*15*
N 16 12	2		
N 16 11	2		
N 16 10	2		
N 16 09	2		
N 16 08	1		
N 16 05	2		
N 16 07	2		
N 16 06	2		
N 16 04	3		
N 02_30	42		
N 16_30	20		
P 29	11		
N 30_29	6		
N 31_29	14		
N 16_31	6		
H 21	2		
P 21	11		
N 02_21	4		
N 16_21	4		
H 22	6		
P 22	7		
N 16_22	3		
N 02_22	4		
H 25	20		
T 25	19		
C 25	28		
P 25	22		
N 25_16	19		
H 27	1		
T 27	12		
C 27	4		
P 27	9		
N 27_16	8		
LIFT	*15*		

APPENDIX D

TABLES OF TASKS, PREDECESSORS AND DURATIONS

Table D1. List of Tasks, Predecessors and Durations for Frame 1(c'ed next pages)

FRAME 1			
TASK ID	**Predecessors**	**Duration**	**Notes:**
C 01	T 01	3	
C 03	T 03	3	
C 06	T 06	5	longer manipulation of sawcut
C 07	T 07	3	
C 09	T 09	3	
C 11	T 11	3	
C 12	T 12	3	
C 13	T 13	3	
C 14	T 14	3	
C 15	T 15	3	
C 16	I 16	3	
C 17	I 17	3	
C 18	I 18	3	
H 01	S	5	more manipulation
H 02	S	3	
H 03	S	2	
H 04	S	3	
H 05	S	2	
H 06	S	7	Complicated element; matching markings w/studs
H 07	S	3	
H 08	S	6	brought from a distant location
H 09	S	1	short element
H 10	S	5	brought from a distant location
H 11	S	3	
H 12	S	2	
H 13	S	3	
H 14	S	1	very close to the framer
H 15	S	2	
H 16	S	2	
H 17	S	2	
H 18	S	2	
H 19	S	5	brought from a distant location
I 16	H 16	3	
I 17	H 17	3	
I 18	H 18	3	
M 01 05	H 01	2	
M 01 10	H 01	3	
M 01 34	H 01	2	

TASK ID	Predecessors	Duration	Notes:
M 02 16	H 02	3	
M 04 11	H 04	3	
M 04 18	H 04	3	
M 05 16	H 05	2	
M 05 17	H 05	2	
M 06 05	H 06	2	
M 06 10	H 06	3	
M 06 13	H 06	2	
M 06 14	H 06	2	
M 06 15	H 06	2	
M 06 34	H 06	2	
M 06 78	H 06	2	
M 08 11	H 08	3	
M 09 78	H 09	2	
M 10 17	H 10	3	
M 10 18	H 10	3	
M 12 15	H 12	2	
N 01 02	P 01, P 02	3	
N 01 05	P 01, P 05	2	
N 01 10	P 01, P 10	2	
N 01 34	P 01, P 34	3	
N 02 16	P 02, P 16	2	
N 03 04	P 03, P 04	5	more nails w/nailgun
N 05 16	P 05, P 16	2	
N 05 17	P 05, P 17	2	
N 06 02	P 06, P 02	4	
N 06 05	P 06, P 05	3	
N 06 10	P 06, P 10	3	
N 06 14	P 06, P 14	2	
N 06 15	P 06, P 15	3	
N 06 19	P 06, P 19	2	edge of the frame: less nails
N 06 34	P 06, P 34	3	
N 06 78	P 06, P 78	4	require precision
N 07 08	P 07, P 08	4	extra time for making the subassembly
N 09 19	P 09, P 19	2	edge of the frame: less nails
N 09 78	P 09, P 78	47	rework times incorporated
N 10 17	P 10, P 17	2	
N 10 18	P 10, P 18	2	

TASK ID	Predecessors	Duration	Notes:
N 11 34	P 11, P 34	2	
N 12 11	P 12, P 11	6	more nails than usual w/nailgun
N 12 15	P 12, P 15	3	
N 13 78	P 13, P 78	4	
N 14 34	P 14, P 34	4	
N 15 12	P 15, P 12	3	
N 18 34	P 18, P 34	3	
N 19 78	P 19, P 78	8	long element; assures enclosure by multiple nailings
N 34 18	P 34, P 18	2	
N 78 11	P 78, P 11	2	
N 78 12	P 78, P 12	2	
P 01	C 01	2	
P 02	H 02	2	
P 03	C 03	2	
P 04	H 04	3	
P 05	H 05, M 01 05, M 06 05	2	
P 06	C 06	5	matching w/vertical studs for enclosure
P 07	C 07	2	
P 08	H 08	2	
P 09	C 09	3	
P 10	H 10, M 01 10, M 06 10	5	more manipulation
P 11	C 11, M 04 11, M 08 11	2	
P 12	C 12, P 11, N 11 34	3	
P 13	C 06, P 12, P 78, M 06 13	2	
P 14	C 14, P 12, P 34, M 06 14	2	
P 15	C 15, M 06 15, M 12 15	2	
P 16	C 16, M 02 16, M 05 16	2	
P 17	C 17, M 05 17, M 10 17, N 05 16	2	
P 18	C 18, M 10 18, M 04 18, N 10 17	4	more manipulation
P 19	H 19	2	
P 34	N 03 04, M 01 34, M 06 34	2	
P 78	N 07 08, M 09 78, M 06 78	2	
T 01	H 01	3	
T 03	H 03	2	

TASK ID	Predecessors	Duration	Notes:
T 06	H 06	3	
T 07	H 07	2	
T 09	H 09	3	
T 11	H 11	2	
T 12	H 12	2	
T 13	H 13	1	
T 14	H 14	2	
T 15	H 15	3	

Table D2. List of Tasks, Predecessors and Durations for Frame 3 (continued in the next pages)

FRAME 3		
TASK ID	**Predecessors**	**Duration(s)**
C 01	T 01, M 01 27	3
C 02	T 02	2
C 04	T 04, M 01 04	1
C 05	T 05	1
C 09	T 09	3
C 10	T 10	1
C 11	I 11	1
C 12	T 12	2
C 13	I 13	1
C 14	I 14	1
C 15	T 15	2
C 21	T 21	4
C 22	I 22	1
C 23	I 23	1
C 24	I 24	1
C 26	T 26	2
C 27	T 27	3
C 29	T 29	2
C 30	T 30	2
C 31	T 31	2
C 32	T 32	4
C 33	T 33	4
C 34	T 34	11
C 37	T 37	2
H 01	S	2
H 02	S	5
H 03	S	1
H 04	S	1
H 05	S	1
H 06	S	1
H 07	S	1
H 08	S	2
H 09	S	2

TASK ID	Predecessors	Duration(s)
H 10	S	1
H 11	S	1
H 12	S	1
H 15	S	1
H 16	S	1
H 17	S	1
H 18	S	1
H 19	S	3
H 20	S	1
H 21	S	1
H 22	S	1
H 24	S	1
H 25	S	2
H 26	S	1
H 27	S	1
H 28	S	2
H 29	S	1
H 30	S	1
H 31	S	6
H 32	S	2
H 33	S	3
H 34	S	3
H 35	S	4
H 36	S	1
H 37	S	4
I 11	H 11, C 10	4
I 13	C 10	8
I 14	C 10	6
I 22	C 21,H 22	2
I 23	C 21	2
I 24	H 24	2
M 01 03	H 01	6
M 01 04	H 01	1
M 01 05	H 01	6

TASK ID	Predecessors	Duration(s)
M 01 06	H 01	2
M 01 13	H 01	1
M 01 14	H 01	1
M 01 17	H 01	1
M 01 18	H 01	1
M 01 19	H 01	1
M 01 20	H 01	1
M 01 25	H 01	4
M 01 26	H 01	4
M 01 27	H 01	2
M 01 36	H 01	4
M 02 03	H 02	1
M 02 06	H 02	2
M 02 17	H 02	1
M 02 18	H 02	1
M 02 19	H 02	1
M 02 20	H 02	1
M 02 21	H 02	4
M 02 22	H 02	1
M 02 23	H 02	1
M 02 24	H 02	1
M 09 28	H 09	4
M 09 29	H 09	3
M 09 30	H 09	2
M 12 13	H 12	1
M 12 14	H 12	1
M 31 28	H 31	5
M 56 10	P 56	4
M 56 12	P 56	7
M 56 15	P 56	7
N 01 13	P 01, P 13	2
N 01 14	P 01, P 14	2
N 01 16	P 01, P 16	1
N 01 17	P 01, P 17	2

TASK ID	Predecessors	Duration(s)
N 01 18	P 01, P 18	1
N 01 19	P 01, P 19	1
N 01 20	P 01, P 20	1
N 01 36	P 01, P 36	2
N 01 38	P 01, P 38	2
N 01 43	P 01, P 43	6
N 01 56	P 01, P 56	3
N 02 16	P 02, P 16	1
N 02 17	P 02, P 17	1
N 02 18	P 02, P 18	1
N 02 19	P 02, P 19	1
N 02 20	P 02, P 20	1
N 02 21	P 02, P 21	5
N 02 22	P 02, P 22	2
N 02 23	P 02, P 23	2
N 02 24	P 02, P 24	3
N 02 31	P 02, P 31	2
N 02 36	P 02, P 36	3
N 02 38	P 02, P 38	6
N 02 40	P 02, P 40	20
N 02 43	P 02, P 43	1
N 02 56	P 02, P 56	14
N 04 03	H 03, C 04	10
N 05 06	H 06, C 05	9
N 07 08	H 07, H 08	5
N 09 39	P 09, P 39	16
N 10 56	P 10, P 56	9
N 11 43	P 11, P 43	1
N 12 10	P 10, P 12	1
N 12 11	P 11, P 12	2
N 12 13	P 12, P 13	3
N 12 14	P 12, P 14	5
N 15 12	P 15	1

TASK ID	Predecessors	Duration(s)
N 21 78	P 21	16
N 25 26 27	N 26 25, C 27	6
N 26 25	C 26, H 25	8
N 29 28	C 29, H 28	7
N 30 29 28	N 29 28, C 30	2
N 31 39	P 39, P 31	5
N 31 40	P 31, P 40	56
N 32 34 33	C 32, C 34, C 33	10
N 35 39	P 35	2
N 36 38	P 36	9
N 37 02	P 37	19
N 37 31	P 37	4
N 38 40	P 40	5
N 39 40	P 40	4
N 43 12	P 43, P 12	1
N 43 78	P 43	3
N 56 12	P 56, P 12	2
N 56 78	P 78	8
N 78 22	P 78, P 22	1
N 78 23	P 78, P 23	1
N 78 24	P 78, P 24	1
P 01	C 01	3
P 02	C 02	2
P 09	C 09	5
P 10	M 56 10, C 10	3
P 11	C 11	2
P 12	C 12, M 56 12	1
P 13	C 13, M 01 13, M 12 13	1
P 14	C 14, M 01 14, M 12 14	2
P 15	C 15, N 12 10, N 12 14, N 12 13, N 12 11, M 56 15	3
P 16	H 16	1
P 17	M 02 17, M 01 17, H 17	2
P 18	H 18, M 01 18, M 02 18	2
P 19	H 19, M 01 19, M 02 19	2

TASK ID	Predecessors	Duration(s)
P 20	H 20, M 01 20, M 02 20	2
P 21	C 21, M 02 21, P 56, P 78	1
P 22	M 02 22, C 22, P 43, P 78	3
P 23	M 02 23, C 23	2
P 24	M 02 24, C 24	3
P 31	C 31	2
P 35	H 35, N 39 40	3
P 36	H 36, M 01 36, N 38 40	1
P 37	C 37, N 31 39, N 31 40, N 02 40, N 02 38, N 02 36, N 02 20, N 02 19, N 02 56, N 02 21, N 02 24, N 02 31	3
P 38	N 25 26 27, M 01 27, M 01 26, M 01 25	4
P 39	N 30 29 28, M 09 30, M 09 29, M 09 28, M 31 28	4
P 40	N 32 34 33, P 39, P 38	16
P 43	N 04 03, M 01 03, M 02 03	1
P 56	N 05 06, M 01 06, M 01 05, M 02 06	2
P 78	N 07 08, P 43, P 56	4
T 01	H 01	9
T 02	H 02	13
T 04	H 04	6
T 05	H 05	5
T 09	H 09	5
T 10	H 10	4
T 12	H 12	7
T 15	H 15	7
T 21	H 21	4
T 26	H 26	2
T 27	H 27	2
T 29	H 29	2
T 30	H 30	3
T 31	H 31	7
T 32	H 32	10
T 33	H 33	19
T 34	H 34	45
T 37	H 37	8

Table D3. List of Tasks, Predecessors and Durations for Frame 4 (continued in the next pages)

FRAME 4		
TASK ID	**Predecessors**	**Duration (s)**
C 02	T 02	2
C 03	T 03	3
C 04	T 04	3
C 05	T 05	4
C 07	T 07	2
C 09	T 09	1
C 15	T 15	2
C 17	T 17	13
C 18	T 18	5
C 27	T 27	5
C 28	T 28	1
C 36	I 36	1
C 38	T 38	4
C 39	T 39	4
C 40	T 40	1
C 41	T 41	2
C 42	T 40	1
C 43	T 43	2
C 44	T 44	1
C 45	T 45	2
C 47	T 47	19
C 48	T 48	18
C 50	T 50	2
C 51	T 51	2
C 52	T 52	2
C 53	T 53	3
C 54	T 54	2
C 55	T 55	2
C 56	T 56	2
C 57	T 57	1
C 58	T 58	1
C 59	T 59	2
C 62	H 62	6

TASK ID	Predecessors	Duration (s)
C 63	T 63	3
H 01	S	2
H 02	S	2
H 03	S	4
H 04	S	2
H 05	S	1
H 06	S	1
H 07	S	1
H 08	S	2
H 09	S	1
H 10	S	1
H 11	S	1
H 12	S	1
H 13	S	1
H 14	S	1
H 15	S	1
H 16	S	1
H 17	S	3
H 19	S	1
H 20	S	2
H 21	S	1
H 22	S	1
H 23	S	1
H 24	S	1
H 25	S	1
H 26	S	1
H 27	S	1
H 29	S	1
H 30	S	1
H 31	S	2
H 32	S	2
H 33	S	2
H 34	S	3

TASK ID	Predecessors	Duration (s)
H 35	S	2
H 36	S	1
H 37	S	5
H 38	S	2
H 39	S	2
H 40	S	3
H 43	S	2
H 44	S	1
H 46	S	3
H 47	S	3
H 49	S	7
H 50	S	2
H 51	S	2
H 56	S	1
H 60	N 17 18	2
H 61	N 27 28	2
H 62	N 09 10	1
I 36	H 36	1
M 01 05	H 01	3
M 01 06	H 01	1
M 01 07	H 01	2
M 01 08	H 01	1
M 01 09	H 01	1
M 01 10	H 01	1
M 01 11	H 01	1
M 01 12	H 01	2
M 01 13	H 01	1
M 01 14	H 01	1
M 01 19	H 01	2
M 01 20	H 01	2
M 01 29	H 01	1
M 01 33	H 01	1
M 01 34	H 01	1
M 01 41	H 01	1
M 01 42	H 01	2

TASK ID	Predecessors	Duration (s)
M 01 46	H 02	1
M 02 15	H 02	2
M 02 16	H 02	1
M 02 21	H 02	1
M 02 22	H 02	1
M 02 23	H 02	1
M 02 24	H 02	2
M 02 25	H 02	6
M 02 26	H 02	2
M 02 35	H 02	1
M 03 06	H 03	1
M 03 08	H 03	1
M 03 11	H 03	1
M 03 12	H 03	1
M 03 13	H 03	1
M 03 14	H 03	1
M 03 19	H 03	1
M 03 20	H 03	1
M 03 21	H 03	1
M 03 22	H 03	1
M 03 29	H 03	1
M 03 33	H 03	1
M 03 34	H 03	1
M 03 35	H 03	1
M 03 36	H 03	1
M 03 37	H 03	1
M 03 46	H 03	1
M 04 24	H 04	1
M 04 25	H 04	1
M 21 51	H 21	2
M 21 52	H 21	1
M 21 53	H 21	1
M 21 54	H 21	2

TASK ID	Predecessors	Duration (s)
M 21 55	H 21	1
M 22 51	H 22	1
M 22 52	H 22	1
M 22 53	H 22	1
M 22 54	H 22	2
M 22 55	H 22	1
M 25 56	H 25	2
M 25 57	H 25	1
M 25 58	H 25	1
M 25 59	H 25	1
M 26 56	H 26	1
M 26 57	H 26	1
M 26 58	H 26	1
M 26 59	H 26	2
M 44 41	H 44	3
M 44 42	H 44	4
M 61 38	H 61	5
M 61 39	H 61	3
M 62 44	H 62	2
M 62 45	H 62	3
M 63 44	P 63	2
M 63 45	P 63	2
N 01 11	P 01, P 11	1
N 01 14	P 01, P 14	2
N 01 19	P 01, P 19	1
N 01 20	P 01, P 20	2
N 01 34	P 01, P 34	2
N 01 40	P 01, P 40	1
N 01 41	P 01, P 41	1
N 01 46	P 01, P 46	1
N 01 62	P 01, P 62	1
N 01 64	P 01, P 64	4
N 01 65	P 01, P 65	4
N 01 66	P 01, P 66	3

TASK ID	Predecessors	Duration (s)
N 01 87	P 01, P 87	3
N 02 01	P 02, P 01	1
N 02 21	P 02, P 21	1
N 02 22	P 02, P 22	1
N 02 23	P 02, P 23	1
N 02 24	P 02, P 24	1
N 02 25	P 02, P 25	1
N 02 26	P 02, P 26	1
N 02 35	P 02, P 35	1
N 02 42	P 02, P 42	1
N 02 43	P 02, P 43	1
N 02 63	P 02, P 63	2
N 03 11	P 03, P 11	1
N 03 14	P 03, P 14	2
N 03 20	P 03, P 20	1
N 03 21	P 03, P 21	2
N 03 22	P 03, P 22	1
N 03 34	P 03, P 34	1
N 03 35	P 03, P 35	1
N 03 36	P 03, P 36	1
N 03 37	P 03, P 37	1
N 03 38	P 03, P 38	1
N 03 39	P 03, P 39	1
N 03 46	P 03, P 46	1
N 03 60	P 03, P 60	2
N 03 64	P 03, P 64	2
N 03 65	P 03, P 65	1
N 03 66	L 03, P 66	3
N 03 87	P 03, P 87	1
N 04 03	P 04, P 03	4
N 04 23	P 04, P 23	2
N 04 24	P 04, P 24	1
N 04 25	P 04, P 25	1
N 04 26	P 04, P 26	1
N 05 06	H 06, C 05	8

TASK ID	Predecessors	Duration (s)
N 07 08	H 08, C 07	8
N 09 10	H 10, C 09	10
N 13 12	H 12, H 13	6
N 15 16	H 16, C 15	9
N 17 18	C 17, C 18	13
N 19 87	P 19	9
N 21 51	P 21, P 51	2
N 21 52	P 21, P 52	1
N 21 53	P 21, P 53	2
N 21 54	P 21, P 54	1
N 21 55	P 21, P 55	1
N 22 51	P 22, P 51	2
N 22 52	P 22, P 52	2
N 22 53	P 22, P 53	3
N 22 54	P 22, P 54	2
N 22 55	P 22, P 55	1
N 25 56	P 25, P 56	1
N 25 57	P 25, P 57	1
N 25 58	P 25, P 58	1
N 25 59	P 25, P 59	1
N 26 56	P 26, P 56	1
N 26 57	P 26, P 57	1
N 26 58	P 26, P 58	1
N 26 59	P 26, P 59	1
N 27 28	C 27, C 28	13
N 29 30	H 29, H 30	1
N 29 31	H 29, H 31	3
N 29 32	H 29, H 32	3
N 33 30	H 30, H 33	4
N 33 31	H 31, H 33	4
N 33 32	H 32, H 33	4
N 34 61	P 34, P 61	4
N 34 62	P 34	8
N 35 61	P 35, P 61	3

TASK ID	Predecessors	Duration (s)
N 35 63	P 35	11
N 36 34	P 36, P 34	3
N 37 35	P 37, P 35	3
N 38 61	P 38, P 61	3
N 39 61	P 39, P 61	2
N 40 62	P 40	3
N 43 63	P 43	3
N 44 40	P 40, P 44	1
N 44 41	P 41, P 44	2
N 44 42	P 42, P 44	2
N 44 43	P 43, P 44	3
N 45 44	P 45	6
N 46 65	P 46	6
N 47 87	P 47, P 87	8
N 48 65	P 48, P 65	7
N 49 03	P 49	14
N 49 04	P 49	6
N 50 03	P 50	5
N 61 63	P 61	12
N 62 44	P 62, P 44	1
N 62 61	P 61	21
N 63 44	P 63, P 44	1
N 65 60	P 65, P 60	2
N 87 60	P 87, P 60	3
P 01	H 01	1
P 02	C 02	4
P 03	C 03	10
P 04	C 04	2
P 11	H 11, M 01 11, M 03 11	1
P 14	H 14, M 01 14, M 03 14	3
P 19	H 19, M 01 19, M 03 19, N 87 60	2
P 20	H 20, M 01 20, M 03 20	3
P 21	H 21, M 02 21, M 03 21	2
P 22	H 22, M 02 22, M 03 22	1

TASK ID	Predecessors	Duration (s)
P 23	H 23, M 02 23	2
P 24	H 24, M 02 24, M 04 24	1
P 25	H 25, M 02 25, M 04 25	1
P 26	H 26, M 02 26	2
P 34	H 34, M 01 34, M 03 34, N 62 44	2
P 35	H 35, M 02 35, M 03 35, N 63 44	1
P 36	C 36, M 03 36	6
P 37	H 37, M 03 37	2
P 38	M 61 38, C 38	1
P 39	M 61 39, C 39	1
P 40	C 40, P 62	1
P 41	M 44 41, M 01 41, C 41	3
P 42	C 42, M 02 42, M 44 42	2
P 43	C 43, P 63	2
P 44	C 44, M 62 44, M 63 44	2
P 45	C 45, M 62 45, M 63 45, N 44 40, N 44 41, N 44 42, N 44 43	7
P 46	H 46, M 01 46, M 03 46, N 65 60	2
P 47	C 47, N 07 08	4
P 48	C 48, N 05 06	8
P 49	N 04 26, N 04 25, N 04 24, N 04 23, N 03 22, N 03 21, N 03 35, N 03 37, N 03 38, N 03 39, N 03 36, N 03 11, N 03 34, N 03 64, N 03 14, N 03 66, N 03 46, N 03 60, H 49	1
P 50	C 50, N 03 20, N 03 87, N 03 60	3
P 51	C 51, M 21 51, M 22 51	1
P 52	C 52, M 21 52, M 22 52	1
P 53	C 53, M 21 53, M 22 53	1
P 54	C 54, M 21 54, M 22 54	2
P 55	M 21 55, M 22 55, C 55	4
P 56	C 56, M 25 56, M 26 56	2
P 57	C 57, M 25 57, M 26 57	1
P 58	C 58, M 25 58, M 26 58	1
P 59	C 59, M 25 59, M 26 59	2
P 60	H 60, P 87, P 65	5
P 61	H 61, P 62, P 63	5
P 62	M 01 09, M 01 10, C 62	1
P 63	M 02 15, M 02 16, C 63	1

TASK ID	Predecessors	Duration (s)
P 64	N 13 12, M 01 13, M 03 13, M 01 12, M 03 12	1
P 65	N 05 06, M 01 05, M 01 06, M 03 06	1
P 66	N 33 30, N 33 31, N 33 32, N 29 31, N 29 32, N 29 30, M 01 29, M 03 29, M 01 33, M 03 33	5
P 87	N 07 08, M 01 07, M 01 08, M 03 08	1
T 02	H 02	8
T 03	H 03	5
T 04	H 04	6
T 05	H 05	5
T 07	H 07	5
T 09	H 09	3
T 15	H 15	5
T 17	H 17	8
T 18	H 17	7
T 27	H 27	3
T 28	H 27	6
T 38	H 38	4
T 39	H 39	2
T 40	H 40	1
T 41	H 40	3
T 42	H 40	2
T 43	H 43	2
T 44	H 44	3
T 45	H 44	2
T 47	H 47	13
T 48	H 47	10
T 50	H 50	11
T 51	H 51	4
T 52	H 51	3
T 53	H 51	4
T 54	H 51	3
T 55	H 51	3
T 56	H 56	3
T 57	H 56	2

TASK ID	Predecessors	Duration (s)
T 58	H 56	2
T 59	H 56	2
T 63	N 15 16	1

APPENDIX E

RESULTS OF CALCULATIONS FOR DETERMINING PROCEDURAL DEVIATIONS OF EACH FRAMER

Table E1. Frame 2, Round 1, Framer 1 - Computation of Compliance Rate

Ideal	**RULE 1**	1
	RULE 2	35
	RULE 3	30
	RULE 4	35
	RULE 5	15
Totals:		116
Legitimate_Skips	**RULE 1**	**0**
(in situ conditions)	**RULE 2**	**3**
	RULE 3	**3**
	RULE 4	**3**
	RULE 5	**1**
Totals:		10
In-Situ Ideal		106
Ignored Rules	**RULE 1**	**0**
	RULE 2	**1**
	RULE 3	**0**
	RULE 4	**1**
	RULE 5	**1**
Totals:		3
Compliance		97%

Table E2. Frame 2, Round 2, Framer 1 - Computation of Compliance Rate

Ideal	**RULE 1**	0
	RULE 2	14
	RULE 3	11
	RULE 4	14
	RULE 5	3
Totals:		42
Legitimate_Skips	**RULE 1**	**0**
(in situ conditions)	**RULE 2**	**0**
	RULE 3	**0**
	RULE 4	**0**
	RULE 5	**0**
Totals:		0
In-Situ Ideal		42
Ignored Rules	**RULE 1**	**0**
	RULE 2	**7**
	RULE 3	**4**
	RULE 4	**7**
	RULE 5	**3**
Totals:		21
Compliance		50%

Table E3. Frame 2, Round 3, Framer 1 - Computation of Compliance Rate

Ideal	**RULE 1**	0
	RULE 2	7
	RULE 3	0
	RULE 4	7
	RULE 5	4
Totals:		18
Legitimate_Skips	**RULE 1**	**0**
(in situ conditions)	**RULE 2**	**0**
	RULE 3	**0**
	RULE 4	**0**
	RULE 5	**0**
Totals:		0
In-Situ Ideal		18
Ignored Rules	**RULE 1**	**0**
	RULE 2	**1**
	RULE 3	**0**
	RULE 4	**1**
	RULE 5	**1**
Totals:		3
Compliance		83%

Table E4. Frame 2, Round 4, Framer 1 - Computation of Compliance Rate

Ideal	**RULE 1**	0
	RULE 2	5
	RULE 3	0
	RULE 4	5
	RULE 5	4
Totals:		14
Legitimate_Skips	**RULE 1**	**0**
(in situ conditions)	**RULE 2**	**0**
	RULE 3	**0**
	RULE 4	**0**
	RULE 5	**0**
Totals:		0
In-Situ Ideal		14
Ignored Rules	**RULE 1**	**0**
	RULE 2	**0**
	RULE 3	**0**
	RULE 4	**0**
	RULE 5	**0**
Totals:		
Compliance		100%

Table E5. Frame 2, Round 1, Framer 2 - Computation of Compliance Rate

Ideal	**RULE 1**	0
	RULE 2	8
	RULE 3	3
	RULE 4	8
	RULE 5	5
Totals:		24
Legitimate_Skips	**RULE 1**	**0**
(in situ conditions)	**RULE 2**	**0**
	RULE 3	**0**
	RULE 4	**0**
	RULE 5	**0**
Totals:		0
In-Situ Ideal		24
Ignored Rules	**RULE 1**	**0**
	RULE 2	**1**
	RULE 3	**0**
	RULE 4	**1**
	RULE 5	**1**
Totals:		3
Compliance		88%

Table E6. Frame 2, Round 2, Framer 2 - Computation of Compliance Rate

Ideal	**RULE 1**	0
	RULE 2	26
	RULE 3	24
	RULE 4	26
	RULE 5	10
Totals:		86
Legitimate_Skips	**RULE 1**	**0**
(in situ conditions)	**RULE 2**	**2**
	RULE 3	**1**
	RULE 4	**2**
	RULE 5	**2**
Totals:		7
In-Situ Ideal		79
Ignored Rules	**RULE 1**	**0**
	RULE 2	**1**
	RULE 3	**1**
	RULE 4	**1**
	RULE 5	**0**
Totals:		
Compliance		96%

Table E7. Frame 2, Round 3, Framer 2 - Computation of Compliance Rate

Ideal	**RULE 1**	0
	RULE 2	4
	RULE 3	0
	RULE 4	4
	RULE 5	3
Totals:		11
Legitimate_Skips	**RULE 1**	**0**
(in situ conditions)	**RULE 2**	**0**
	RULE 3	**0**
	RULE 4	**0**
	RULE 5	**0**
Totals:		0
In-Situ Ideal		11
Ignored Rules	**RULE 1**	**0**
	RULE 2	**1**
	RULE 3	**0**
	RULE 4	**1**
	RULE 5	**1**
Totals:		3
Compliance		73%

Table E8. Frame 2, Round 4, Framer 2 - Computation of Compliance Rate

Ideal	**RULE 1**	0
	RULE 2	14
	RULE 3	10
	RULE 4	14
	RULE 5	9
Totals:		47
Legitimate_Skips	**RULE 1**	**0**
(in situ conditions)	**RULE 2**	**0**
	RULE 3	**0**
	RULE 4	**0**
	RULE 5	**0**
Totals:		0
In-Situ Ideal		47
Ignored Rules	**RULE 1**	**0**
	RULE 2	**0**
	RULE 3	**0**
	RULE 4	**0**
	RULE 5	**0**
Totals:		0
Compliance		100%

Table E9. Frame 2, Round 5, Framer 2 - Computation of Compliance Rate

Ideal	**RULE 1**	0
	RULE 2	5
	RULE 3	0
	RULE 4	5
	RULE 5	4
Totals:		14
Legitimate_Skips	**RULE 1**	**0**
(in situ conditions)	**RULE 2**	**0**
	RULE 3	**0**
	RULE 4	**0**
	RULE 5	**0**
Totals:		0
In-Situ Ideal		14
Ignored Rules	**RULE 1**	**0**
	RULE 2	**0**
	RULE 3	**0**
	RULE 4	**0**
	RULE 5	**0**
Totals:		0
Compliance		100%

Table E10. Frame 2, Multiple Rounds Results, Average Compliance Rate for Framers

	In-Situ Ideal	Ignored Rules		Percent Compliance
Round1	106	3	F	97%
Round2	42	21	R M	50%
Round3	18	3	R	83%
Round4	14	0	1	100%
Avg. Compliance Framer 1				**83%**
Round1	24	3	F	88%
Round2	79	3	R	96%
Round3	11	3	M	73%
Round4	47	0	R	100%
Round5	14	0	2	100%
Avg. Compliance Framer 2				**90%**

Table E11. Frame 1, Multiple Rounds Results, Average Compliance Rate for Framers

	In-Situ Ideal	Ignored Rules		Percent Compliance
Round1	37	7	F	81%
Round2	12	0	R	100%
Round3	6	0	M	100%
Round4	71	0	R	100%
Round5	47	10	1	79%
Avg. Compliance Framer 1				**92%**
Round1	35	0		100%
Round2	72	14	F	81%
Round3	10	0	R	100%
Round4	26	0	M	100%
Round5	19	10	R	47%
Round6	13	3		77%
Round7	62	0	2	100%
Avg. Compliance Framer 1				**86%**

Table E12. Frame 3, Multiple Rounds Results, Average Compliance Rate for Framers

	In-Situ Ideal	Ignored Rules		Percent Compliance
Round1	98	55	F R A M E R 1	44%
Round2	21	0		100%
Round3	56	0		100%
Round4	45	0		100%
Round5	14	0		100%
Avg. Compliance Framer 1				**89%**
Round1	13	3	F R A M E R 2	77%
Round2	63	0		100%
Round3	53	14		74%
Round4	19	10		47%
Round5	14	0		100%
Round6	74	0		100%
Round7	76	0		100%
Round8	32	0		100%
Avg. Compliance Framer 2				**87%**

Table E13. Frame 4, Multiple Rounds Results, Average Compliance Rate for Framers

	In-Situ Ideal	Ignored Rules		Percent Compliance
Round1	123	2	FRAMER 1	98%
Round2	28	9		68%
Round3	59	13		78%
Round4	26	13		50%
Round5	20	0		100%
Round6	25	0		100%
Round7	80	0		100%
Round8	48	0		100%
Round9	51	0		100%
Avg. Compliance Framer 1				**88%**
Round1	19	3	FRAMER 2	84%
Round2	23	0		100%
Round3	55	0		100%
Round4	24	3		88%
Round5	43	0		100%
Round6	16	3		81%
Round7	86	0		100%
Round8	30	0		100%
Round9	85	16		81%
Round10	98	0		100%
Avg. Compliance Framer 2				**95%**