House Completion Time in Australia:

Workflow Planning Approach

A thesis submitted in fulfilment of
the requirements for the degree of
Doctor of Philosophy

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March 2011

Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and, any editorial work, paid or unpaid, carried out by a third party is acknowledged.

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2011

ABSTRACT

The Australian house building industry has seen an increase in the average house completion time in the past decade. This increase in some Australian states was quite dramatic. For instance, Western Australia faced a seventy percent increase in the average house completion time during this period. Since houses make up more than seventy-five percent of dwellings in Australia, this increase affected a large proportion of housing supply in the country.

This research addresses this issue at industry and company level by investigating house completion time using a workflow-based planning approach. For this purpose, a national and five State case studies (Victoria, New South Wales, Queensland, Western Australia and South Australia) are used at industry level. At company level, production house building is adopted for the study.

The research starts with possible explanations for changes in house completion time suggested by activity-based and workflow-based planning approaches. The association between the house building industry's production rate and the average house floor area, with completion time, is investigated. Then the trends of number of houses under construction and average house completion time are compared and their correlation is examined.

Investigation of the relationship between average house completion time, number of house completions and number of houses under construction is undertaken by comparison between predicted number of houses under construction using Little's law and actual data. A two-phase relationship between average house completion time and number of houses under construction is also explored.

Research at company level includes modelling of an actual house building process, simulation of different operational strategies and exploration of their effects on house completion time. The strategies investigated in the research are the control of workflow, control on construction commencement and having different house options in the process.

The result of research at industry level shows that there is a strong correlation between average house completion time and number of houses under construction. Little's law predicts the number of houses under construction by a small error and it holds true for the national and State house building industries. The existence of a two-phase relationship between house completion

time and number of houses under construction is demonstrated and house building industry capacity is estimated for the whole country and different States. This is the maximum number of houses that the industry can work on without increasing the completion time.

According to this research, average house completion time in Australia is directly influenced by the workflow in the house building industry when the industry is over capacity. It is shown that the industry works like a production system and a workflow-based planning approach can explain its dynamics. Further, the estimated capacities for house building industry in Australia and its States can be used as benchmark for assessing of the effectiveness of different policies and changes in the industry.

At company level, the simulation of different levels of workflow shows that constant workflow returns constant completion time. Reducing the construction commencement intervals in order to achieve higher resource utilization may increase house completion time dramatically. Further, when the new house option is smaller than the current options, its completion time fluctuates between its minimum completion time and the completion time of the largest house option. The modelling also shows that, in the case of the launch of a house option larger than the current options, queues in the production operation are inevitable and the completion time of all house options grows infinitely.

Therefore, introduction of a new house option to a production process can have severe consequences for a builder. It can dramatically increase the completion time of the houses or prevent the builder achieving the desired completion time. Thus, to avoid such consequences, it is recommended that any variation in the house option should be considered carefully and the whole production process should be revised accordingly.

To summarise, the research investigates house completion time in Australia and highlights the effect of workflow on this parameter at industry and company level. It demonstrates the applicability of a workflow-based planning approach in the house building industry and recommends it for use by housing policy makers, house builders and housing researchers for analysis of industry's dynamics and understanding of house building process.

Acknowledgments

First, I would like to thank my supervisor, Professor Ron Wakefield, for his invaluable advice throughout my research and for his substantial support by providing me a PhD scholarship.

My thanks are also extended to my co-supervisor, Associate Professor Nick Blismas, for his constructive comments on the thesis and for our continuous discussions on research.

I would like to acknowledge the efforts undertaken by Mr David Signorelli in the Australian Bureau of Statistics for publication of an article on “average quarterly completion times for new houses” which ignited the main question of this research and I would like to greatly thank him for providing me with house completion time data.

I also would like to acknowledge the support provided by staff at RMIT University and School of Property, Construction and Project Management. Special thanks go to Mr Robert Sheehan for his editorial comments. I am also grateful for my fellow PhD colleagues Agustin Chevez, Supaporn Chalapati, Ting Kwei Wong, Pon Vajiranivesa, Ruttigone Loh, Atif Ali, Tracy Ng and Mohammad Ali Noor for making this journey easier and more enjoyable, for their support and for the fruitful discussions that we had.

I would like to thank my dad for those very first times that he took me to a local bookshop and for the endless encouragement that I received from him in my life, my mum for her infinite love and patience while I was thousands of kilometres away, my brother for his continuous support and my sister for being with me when I most needed her.

Last, but definitely not least, I would like to thank Aida, my wife, who has been patient, understanding and supportive throughout the writing of this thesis. She changed my life, accelerated the pace of my work, mixed every single step of my work with love and without her this could never be done.

To my dad,

Ghorban Ali Gharaie

TABLE OF CONTENTS

FIGURES

TABLES

1 CHAPTER ONE – INTRODUCTION

"The challenges of demand pressures and poor housing affordability are likely to remain unless there is a significant supply-side reform" (National Housing Supply Council, 2010a).

1.1 Background to the research

Housing supply and the issues around it have become a focal point in the Australian housing sector. According to the National Housing Supply Council (NHSC) (2010a), the gap between housing demand and supply in 2010 was 202,400 houses and the gap is expected to reach 334,100 by 2015. NHSC is not the only institute identifying supply shortage in the market. According to ANZ Bank (2010), the housing market has been suffering from a housing shortage since 1998 and the estimated shortage in 2010 was approximately 200,000 homes. The Housing Industry Association (HIA) has also been reporting under-supply in the market for a long time (Housing Industry Association, 2010b).

The shortage of housing supply leads to increasing housing prices and worsening housing affordability. To investigate housing supply, one needs to understand the housing supply pipeline and its characteristics. The housing supply pipeline consists of six stages, namely, *future urban designation*, *specific use zoning*, *structure planning*, *development/subdivision approval*, *civil works and issue of title*, and *building approvals and completion* (National Housing Supply Council, 2010a). Between these six stages, the first five lead to land release to the housing market and attract the most attention in the housing sector. However, the housing supply is not completed without the final stage in which the house is added to the land. One aspect of this stage is the house completion time.

For the Australian house building industry, house completion time has serious investment implications and thus, it is always a major concern for all stakeholders. In this industry, buyers remain financially and emotionally engaged in the process while waiting for their home to be delivered and any increase in completion time results in further capital investment, more management effort, and reduced customer satisfaction.

According to the Australian Bureau of Statistics (ABS) (2008),the house building industry in Australia has experienced an increase in the average completion time of houses in the past decade. The average completion time for new houses at the beginning of 2000 was 1.8 quarters, reaching 2.4 quarters by the end of 2008. These figures show that house buyers had to wait 35 percent longer in 2008 than in 2000. The increase in some States was more dramatic. For instance, Western Australia has faced a 70 percent increase during the same period.

Considering that houses make up more than 75 percent of all dwellings in Australia (Australian Bureau of Statistics, 2006a), these figures show the importance of research on house completion time. However, finding solutions to the increase in completion time requires a proper understanding of its major influencing factors.

House completion time is an issue related to housing studies. However, it has not received much attention from the researchers in this area. This can be explained by three reasons. First, the completion time is related to housing supply, but the focus of housing studies is on the demand side of the housing market rather than supply. Second, housing supply studies rarely investigate the quality of supply, including the completion time. Third, housing supply usually is represented by the number of housing starts. Thus, the completion time, which is related to housing completion, is ignored.

While completion time did not attract much attention in housing studies, it is one of the main issues in construction management research. The concern over completion time led to the development of different construction planning techniques which can be classified into two approaches, namely, the activity-based planning approach and the workflow-based planning approach (Sawhney et al., 2009).

According to the activity-based planning approach, project completion time is affected by duration of activities, and these durations can be influenced by an activity's scope of work and production rate of resources. Therefore, completion time can be affected by these two parameters. On the other hand, the workflow-based planning approach considers construction projects as a series of work processes and places equal emphasis on the workflow processes and the connection between them. With this view, completion time can be affected by workflow variability and reliability, buffers and work in process.

The limitations of the activity-based planning approach, and potentials of the workflow-based planning approach, in explaining the influencing factors on completion time are extensively discussed in construction management literature. However, these efforts are limited to the investigation of completion time at project or production level and the only attempt to explain changes in completion time at industry level is in research undertaken by Bashford et al.(2005).

Building on Bashford et al.'s (2005) work, this research seeks reasons behind the changes in house completion time in Australia. The researcher hopes this research will help industry practitioners and policy makers to understand better the house building industry and its dynamics and, therefore, improve the industry through greater efficiency, greater sustainability, and, the production of sufficient housing supply.

1.2 Research aim, objectives and contributions

The main aim of the research is the workflow analysis of house completion time in Australia. However, the limitations of the activity-based planning approach are also discussed in the research.

In order to reach this aim, five objectives were set for the research. They start with possible explanations for the changes in house completion time according to activity-based and workflow-based planning approaches. The shortcomings of the former, and the potentials of the later, are discussed. Then the workflow-based planning approach is further investigated. Little's law is explained and used for achieving the second research objective which was the investigation of the relationship between average house completion time, number of house completions and number of houses under construction.

The third objective explored the two-phase relationship between average house completion time and number of houses under construction. It continues with implications of this relationship and introduces the average house completion time as an indicator of house building industry capacity. Finding the exact capacity of the house building industry in Australia and its different States is part of this objective.

Investigation of house completion time cannot be completed without addressing the issues at company level. Therefore, as the fourth objective, an actual house building process is modelled. This model is used as a platform for the next step of the study.

Using the workflow-based planning approach at company level is the fifth objective. This commences with exploration of the effect of control on the number of houses under construction on house completion time. The construction commencement interval decision is another operational strategy whose effect on house completion time is investigated and its importance is highlighted. Finally, the operational strategy of offering different house design options to the customers is examined. This strategy is a normal practice among house builders in Australia and the research demonstrates its consequences regarding completion time.

1.3 Research design

The research design is based on a framework proposed by Creswell (2009). This framework consists of three elements including philosophical worldview, strategy of inquiry and research method. As is explained in chapter three (section 3.3.1), the philosophical worldview of the research is postpositivist. The research identifies itself with an objectivist epistemology and its ontology is realism.

Since the research seeks to gather factual data and studies relationship between facts and how facts and relationships accord with theories, a quantitative strategy of inquiry is chosen. However, the research strategy is not limited to a decision between quantitative and qualitative modes of inquiry. Yin (2009) suggests that there are five common strategies namely survey, experiment, archival analysis, histories and case studies. A quantitative case study strategy was selected according to form of research question, level of control on events and focuses on contemporary events.

The research at industry level tests hypotheses derived from existing knowledge, has external validity, investigates cause and effect, and has a broad scope of proposition. Therefore, multiple case study design was chosen for this part of study. The research at company level generates new hypotheses, has internal validity, seeks causal mechanisms and has a deep scope of proposition. Thus, single case study design was adopted for this part of research.

The multiple case studies consist of the house building industry in the five largest States in Australia and a national case. The State cases are Victoria, New South Wales, Queensland, Western Australia and South Australia. These States contain 95 percent of country's population. The national case is the Australian house building industry which sums up all the State cases and the remaining parts of the country. The data from these cases are obtained from the Australian Bureau of Statistics and include average house completion time, average house floor area, number of house completions and number of houses under construction.

The single case study is an actual house building process. This process is modelled using a general purpose simulation software called Simul8. The data for this case study are collected through site observations, interviews with sub-contractors and crews, interview with site manager and document analysis. These data include activity durations, the logic and relationship between activities, list of sub-contractors and crews, general schedule of one house construction, materials needed for activities and their related costs, and idle time in the process. Different operational strategies are then simulated and results are collected. The focus of the study is mainly on house completion time. However, parameters such as resource utilization and project duration are also considered.

1.4 Research limitations

This research investigates house completion time in Australia and applies the workflow-based planning approach to this that matter. There are three aspects of the research that limit its scope. The first aspect is the Australian context. All the data and analysis in the research are related to Australia and its different States. This is a country surrounded by water and without a land border with any other country. This geography has restricted the movement of human resources to the country for thousands of years and it is still a main factor in making it a closed system. Generalisation to a broader context may not be possible because other countries may not work as a closed system.

The second limiting aspect is the focus on houses. *House* has a specific definition in the research (section 3.3.3) and mainly refers to detached dwellings. It does not include other kinds of dwellings such as apartments or units. Although houses make up more than seventy-five percent of the dwellings in the country, this research does not intend to generalise its results to all dwelling constructions and limits them to houses and the house building industry.

The third limitation stems from the approach taken by the research. House completion time is analysed using the workflow-based planning approach, and the potentials of this approach in analysis of house building industry dynamics are highlighted. However, this is not the only approach that can be taken for the investigation of house completion time. Further, the research at company level is undertaken using this approach and a workflow model is employed. Therefore, the result of the research is more useful for builders with a continuous operation.

1.5 Outline of the thesis

Chapter one provides an introductory explanation of the research background. It summarizes the research aim, objectives and contributions and overviews the research design. The thesis outline, publications, abbreviations and acronyms are also included in this chapter.

Chapter two reviews the literature related to house completion time. The literature is divided into two areas, namely, housing literature and construction management literature. The construction management literature covers construction planning techniques. These techniques are classified as activity-based planning and workflow-based planning. The activity-based planning approach includes network techniques, graphical techniques and operation research. The literature related to the workflow-based planning approach is reviewed according to parameters affecting workflow. The parameters reviewed in this chapter are workflow variability and reliability, buffers and work in process.

Chapter three starts with the clarification of the research aim and objectives, and continues with the outline of the research design and the rationale for its selection. The research philosophical worldview, the research strategy of inquiry and the research method are discussed in this chapter. Case study selection, the description and detail of case studies, data definitions and data collection are also included in chapter three.

Chapter four addresses the first objective of the research and investigates the possible explanations for changes in house completion time. These explanations are derived from the literature and specifically are based on the activity-based planning approach and the workflow-based planning approach. Also discussed in this chapter is then association between housing parameters such as average house floor area, number of house completions and number of houses under construction with average house completion time.

Chapter five addresses the second objective of the research. This chapter uses the workflow-based planning approach and investigates the relationship between three parameters of average house completion time, number of house completions and number of houses under construction. For this purpose, Little's law in operation planning is adapted to suit the house building industry. The applicability of this law is shown in chapter five through the prediction of number of houses under construction using the other two parameters.

These predictions are compared with the actual data. Error metrics, r-square and visual comparison are used as the indicators of the accuracy of these predictions. As a result, it is shown in this chapter that the behaviour of the house building industry can be predicted using Little's law. Further preliminary studies on the two-phase relationship between house completion time and number of houses under construction are also reported in this chapter.

Chapter six relates to third objective of the research. It further investigates the two phase relationship between average house completion time and number of houses under construction. It explores the implications of workflow-based planning approach for the house building industry. This implication includes the determination of the critical number of houses under construction and minimum house completion time for all case studies. Then each case study is analysed according to the workflow-based planning approach and the validity of the determined critical number of houses under construction and minimum house completion time is demonstrated.

Chapter seven takes the studies to micro level and addresses the final two objectives of the research. While the previous chapters focus on house completion time at the industry level and investigate the cases studies at State and national level, chapter seven explores the effect of number of houses under construction, construction commencement intervals and house design options, on house completion time at company level. In this chapter, an actual house building process is modelled and different operational strategies are simulated. The result shows the effect of control on the number of houses under construction and the importance of the construction commencement decision. It also highlights the effect of variation in design on house completion time.

Chapter eight summarises the previous chapters and outlines the conclusions. The conclusions for all objectives, and the final conclusion of the research, are described in this chapter. Then the research implications for theory, practice and future research are explained.

Appendices consist of appendix A and B. Appendix A includes actual data on average house completion time, average house floor area, number of house completions and number of houses under construction in five States and the whole country. The predicted number of houses under construction for all the case studies is listed in Appendix B. These predictions are undertaken using different moving average lengths and different lags.

1.6 Publications

Some parts of the research results were published and following are the citations for the publications:

GHARAIE, E., WAKEFIELD, R. & BLISMAS, N. 2010. Explaining the Increase in the Australian Average House Completion Time: Activity-based versus Workflow-based Planning. *Australasian Journal of Construction Economics and Building*, 10, 34-49.

GHARAIE, E., WAKEFIELD, R. & BLISMAS, N. 2010. The effect of house design variation on the completion time in a production building operation. *COBRA 2010*, 2-3 Sep 2010, Paris, France.

GHARAIE, E., WAKEFIELD, R. & BLISMAS, N. 2010. The impact of construction commencement intervals on residential production building. *International Conference on Construction and Real Estate Management*, 1-3 Dec 2010, Brisbane, Australia.

1.7 Abbreviations and acronyms

This section sets out the abbreviations and acronyms used in the research.

A	Actual
ABS	Australian Bureau of Statistics
AHCT	Average house completion time
Aus	Australia
CT	Cycle time
L	Lag
MAD	Mean absolute deviation
MAPE	Mean absolute percentage error
MSE	Mean square error
NHC	Number of house completions
NHSC	National Housing Supply Council
NHUC	Number of houses under construction
NSW	New South Wales

P	Predicted
Qld	Queensland
SA	South Australia
t	Time
TH	Throughput
Vic	Victoria
WA	Western Australia
WIP	Work in process

1.8 Chapter summary

The chapter started by explaining housing supply shortage as a broad issue and emphasised the need for reform in the supply side of the market. Then the importance of research on house completion time was articulated. The research aim and objectives were briefly detailed and a blueprint of the research design was described. The thesis outline, citation of research publications, abbreviations and acronyms used in the research were also included in this chapter.

The next chapter commences the research journey by seeking out existing knowledge through a review of the literature related to the research aim and objectives.

2 CHAPTER TWO - HOUSE COMPLETION TIME IN THE LITERATURE

2.1 Introduction

The previous chapter explained the importance of house completion time investigation and highlighted the recent increase of this parameter in the housing sector in Australia. This chapter explores the existing knowledge and theories about the influencing factors on completion time. This exploration is undertaken in two different areas in the literature.

Since the main aim of the research is the investigation of house completion time, the first area to look at is the housing literature. This area may suggest some explanations for the changes in completion time using housing parameters.

The second area is selected due to the nature of house building which is a construction project. This area of research and literature in the construction management literature focuses on construction project planning. It is explored for suggestions about the influencing parameters on house completion time and related hypotheses for its changes in the Australian house building industry.

The following section starts this exploration of the literature in the housing area.

2.2 Completion time in housing literature

Although house completion time is a parameter related to housing, the exploration in this area showed a lack of research on this issue. This can be explained by three reasons. First, most of the housing research is economic analysis of the housing market and housing demand is an important economic factor in these analyses. Therefore, housing literature is more focused on the demand side of the housing market (Dipasquale, 1999, Glaeser, 2004, Gyourko, 2009). However, house completion time is a matter related to housing supply and thus it is not mentioned in most of housing literature.

Second, although the gap in research on housing supply was identified by the researchers and increasing attention is being diverted toward its understanding (Murphy, 2008), housing supply literature does not discuss the quality of housing supply and the time related to house completion. This literature usually covers the issues related to elasticity of supply and the effective factors on supply. One example of this approach toward housing supply is the state of supply report by Australian National Housing Supply Council (2010) that described the factors affecting supply of new dwellings as the construction cost, infrastructure costs, land availability, land release and development processes.

Other examples of studies that emphasize the estimation of price and cost elasticities include Topel and Rosen (1988), Dipasquale and Wheaton (1994), Mayer and Somerville (2000), Quigley and Raphael (2005), Glaeser et al. (2006), Gyourko and Saiz (2006), Wheaton and Simonton (2007), Glaeser et al (2008) and Grimes and Aitken (2010). Recently a study on Melbourne housing supply was published in which the effect of planning and regulatory change on housing supply were investigated (Goodman et al., 2010).

Third, housing supply is usually measured by the number of housing starts (Falk and Lee, 2004). Considering the number of starts as a robust proxy measure for housing supply overlooks the construction process and changes in housing inventories during and after construction. Consequently, the completion time is ignored. Therefore, the housing literature, and even the literature on housing supply, does not acknowledge house completion time as an important parameter in the housing market.

All the papers mentioned above follow this suit and consider number of starts as equivalent to housing supply. These papers assume that the houses whose construction is started are completed after a lag and, therefore, there is no difference between housing starts and completions. Coulson (1999) argues that while the number of housing starts is influenced by housing market variables, the number of completions depends on the unfinished housing inventory in the house building industry and the technology of construction. Therefore, number of housing completions is different from number of house starts, and it more accurately represents the state of new supply of housing.

Some papers that address the number of house completions as the best measure of housing supply include Boorah (1993), Lee (1992), Coulson and Richard (1996), Coulson (1999) and Falk and Lee (2004).

To summarize, this section showed that house completion time in the housing literature is ignored because of three reasons. First, the completion time is related to housing supply but the focus of housing literature is on the demand side of the housing market rather than supply. Second, the housing supply literature is concerned with the effective factors on supply and price, or cost elasticity. This research rarely investigates the quality of supply including, the completion time. Third, housing supply usually is represented by the number of housing starts. Thus, the completion time which is related to the housing completions is ignored.

While housing completion time is not sufficiently discussed in the housing literature, it is a focal point in the construction management literature. Completion time and its related issues have been at the centre of project planning issues and have been discussed for a long time. The next section explores these planning methods and approaches and investigates their possible applicability in relation to house completion time.

2.3 Completion time in construction management literature

Completion time is the subject of research on construction project planning and scheduling. The planning approaches can be classified to two categories (Sawhney et al., 2009). The first category of planning considers construction projects as a connected network of activities which can be controlled and improved individually. In this approach, the implementation of a set of management techniques on the activities leads to successful management of the whole project (Howell et al., 1993, Bertelsen and Koskela, 2004, Bashford et al., 2005). This category is known as "task-based planning" or "activity-based planning": in this research the term "activity-based planning" is used to refer to this set of planning techniques.

The second category of planning methods construes construction projects as a series of work processes. In this approach, an equal emphasis is placed on work processes and the connection between them (Sawhney et al., 2009). Therefore, the project manager is required to see the project as interconnected processes and manage the flow of work between these processes (Koskela, 1992, Tommelein et al., 1999, Koskela, 2000, Walsh et al., 2007). This approach is called "workflow-based planning" in this research.

The following section investigates applications and shortcomings of these planning approaches in housing construction and explores the possible influencing factors on house completion time.

2.3.1 Activity-based planning approach

Among construction projects, house building projects belong to a class of projects in which the construction crews are often required to repeat the same work in various locations, moving from one location to another (Hyari and El-Rayes, 2006). These projects are known as repetitive construction projects. These kinds of projects can be divided to two categories (Hegazy and Wassef, 2001).

The first category includes projects that are repetitive due to repetition of unit work throughout project. In this category, the units have physical significance (Ranjbaran, 2007). High rise buildings and volume house building projects belong to this category. The second category of repetitive projects comprises projects that are repetitive due to their geometrical layout. Highways, tunnels and pipeline construction projects fall in this category (Long and Ohsato, 2009).

Different scheduling techniques were developed to address the issues around time, cost and resource continuity in this type of project. These techniques are classified as "network scheduling", "graphical scheduling" and "operation research" techniques. The following sections discuss the application of these techniques in the repetitive construction alongside with their limitations.

Network scheduling techniques

The network techniques of scheduling are the traditional methods of construction project scheduling and have been used in the industry for a long time (Mattila and Park, 2003). These techniques identify the critical activities that affect the project duration and therefore, are easy for practitioners to understand (El-Rayes, 1997). Critical path method (CPM) and project evaluation and review technique (PERT) are the most common techniques in this class that have widespread use in the construction industry.

The main difference between CPM and PERT is on the time estimates of the activity durations. The activity durations are considered as deterministic in CPM, while PERT models them as random variables (Yang, 2002). The detailed description of these techniques and their evolution over the time can be found in Harris (1978), O'Brien (1969) and Moder et al. (1983). Although network techniques were used on countless projects, they were found inadequate in repetitive projects (Suhail and Neale, 1994, Harmelink, 1995, Harris, 1996, Harris and Ioannou, 1998, Harmelink and Rowings, 1998).

These techniques need a large number of activities and connections to model a simple repetitive project. This makes the network extremely complex and detailed. This complexity can be seen in an example discussed by Carr and Meyer (1974). In this example, the scheduling of construction of 200 house units is considered. The building of each unit is undertaken through 24 activities. Thus, the number of activities for the whole project would be the 200 times repetition of these 24 activities. This makes a network of 4800 activities which is highly complex. The issue of shortcoming of network scheduling techniques due to the number of activities is further investigated by Chrzanowski and Johnston (1986), Reda (1990) and Clough et al.(Clough et al., 2000).

CPM or PERT networks do not determine the resources needed for implementing activities. These techniques only focus on the activities and their connections. Resources, their locations and sequences do not appear in the network schedule (Birrell, 1980, Stradel and Cacha, 1982, Rowings and Rahbar, 1992). Thus, the resource continuity is ignored by these techniques.

In house building construction, similar to other repetitive projects, the crews are often involved in moving from one repetitive unit to the next and they should be scheduled to be able to move promptly, without delay (El-Rayes, 1997). However, according to network techniques, the activities are scheduled to start at the earliest possible time. This makes the crews with faster production rate wait for the predecessor crews to finish their jobs and, therefore, waiting time and crew idleness is inevitable (Harris and Ioannou, 1998).

To cover these shortcomings, researchers have tried to use graphical scheduling techniques in which resource continuity and the location of the resources are visually realized.

Graphical scheduling techniques

The graphical scheduling techniques were developed to address the difficulties with network techniques, particularly in scheduling repetitive projects. In these techniques, a repetitive project is modelled by a two dimensional graph in which the x-axis plots time and the y-axis plots the progress of the activities in terms of unit of repetition. Each activity is represented by an inclined line in the graph whose slope is the activity production rate.

The output of these techniques is an easy to read plot of what will happen to the project from the beginning to the end (Mattila and Park, 2003). These techniques aim at maintaining the resource continuity and the schedule is driven by resource constraints. Therefore, they have a significant advantage over network techniques in scheduling repetitive projects, including housing construction (Vorster et al., 1992).

Line of balance (LOB) is the most common method in this category of scheduling. Other graphical methods which follows the same principles as LOB include linear scheduling method (LSM) (Johnston, 1981, Chrzanowski and Johnston, 1986, Harmelink, 1995), vertical production method (VPM) (O'Brien, 1975), repetitive activity scheduling (Rowings and Rahbar, 1992), time space scheduling method (Stradel and Cacha, 1982) and disturbance scheduling technique (Whiteman and Irwing, 1988).

LOB was originated in the early 1940s, by the Goodyear Company and developed by the US Navy in 1952. This method was applied in repetitive housing units by the National Agency of the United Kingdom in the 1960s (Yang, 2002). In short, graphical scheduling techniques have been in use for many years.

However, the development and acceptance of these techniques by the industry has been much slower and more limited than for network techniques. Al Sarraj (1990) and Suhail and Neale (1994) argue that this is because these techniques have a limited usefulness for industry due to the lack of computerization (Yi et al., 2002). Further, finding critical activities that affect the project duration is more complicated in these methods (Harmelink and Rowings, 1998, Harris and Ioannou, 1998, Mattila and Park, 2003, Kallantzis et al., 2007).

Another limitation that these techniques face is scheduling non-repetitive activities. These kinds of activities must be scheduled using network techniques and then incorporated into the graphical schedule (Harmelink, 1995, Arditi et al., 2002).

While graphical techniques focus on resource continuity, they ignore the circumstances of workflow and, thus, variability in the resources production rate or in the repetitive units cannot be modelled and managed using these techniques.

Operation research techniques

Another set of techniques in scheduling repetitive projects was developed using operation research methods. These techniques recently became the most popular approach for scheduling these kinds of projects. In this approach, the optimization of time or cost of the project is the main aim of the planner. However, this objective is subject to resource availability and continuity. The methods that fall into this category include linear programming, dynamic programming, and heuristic and meta-heuristic algorithms.

Linear programming: The first use of linear programming (LP) in housing projects was made by Perera (1983). As was mentioned earlier, resource constraints are the main concern in repetitive projects. Perera tried to address this issue by adding resources (crew and material) availability as a constraint to the model and maximizing the rate of construction as the objective function.

Further, a time-cost trade off was modelled using linear programming in a repetitive project (Reda, 1990). However, this model was subject to some limitations, which stemmed from the model's assumptions. The assumptions were: 1) there was no lag between activities; 2) the production rate of resources was constant; and 3) no work interruption was allowed.

Recently a multi-objective linear programming model was developed by Ipsilandis (2007) for scheduling repetitive projects. In this model the project's duration, the idle time of resources and the delivery time of repetitive units were considered.

Dynamic programming: Early applications of dynamic programming in scheduling repetitive projects include the models for the optimization of the overall project duration under the requirement of continuous resource utilization. In these models, the activities were assumed to be in a simple activity chain (only one predecessor and one successor) and they do not share any resources (Selinger, 1980, Russell and Caselton, 1988).

The objective of minimum project duration was replaced by minimum total cost by Moselhi and El-Rayes (1993). Both indirect and direct costs were considered in this model, and the learning curve effect and the impact of weather on productivity of resources were taken into account.

The assumption of serial activities was removed from dynamic programming models by Eldin and Senouci (1994) and Senouci and Eldin (1996). However, resource sharing was not allowed in this model. The objective function of this model was also the minimization of overall cost.

The minimum project duration was also the objective function for a dynamic programming model developed by El-Rayes and Moselhi (2001). This model was designed to find an optimum crew formation and interruption option that leads to minimum project duration.

An objective oriented model using dynamic programming was developed by Moselhi and Hassanein (2003). This model was capable of considering multiple successors and predecessors with specified lead and lag times, the effect of weather, the effect of learning curve on crew productivity and variations of workflow from one unit to another.

Heuristic and meta-heuristic algorithms: None of the cost optimization methods using linear and dynamic programming can handle non-serial activities, except the model developed by Senouci and Eldin (1996) (Hegazy and Wassef, 2001). Linear programming and dynamic programming cannot guarantee the optimum solution and they might fall in local optima (Li and Love, 1997). Further, these methods are not capable of dealing with complex projects due to the enormous number of decision variables and non-linear constraints (Long and Ohsato, 2009). Thus, heuristic and meta-heuristic methods were developed for scheduling repetitive projects.

Genetic algorithm (GA) is a non-traditional optimization technique and one of the meta-heuristic methods that was proven efficient in searching complex solution spaces and finding the global optimum. This method employs the survival of the fittest approach to find the optimum solution between possible solutions (Hassanein, 2003).

GA was used in a research by Hegazy and Wassef (2001) for determining the minimum total cost of a project. This approach was further developed by Hegazy and Kamarah (2008) specifically for high-rise construction. The use of GA was explored moreover by Hyari and El-Rayes (2006) and Long and Ohsato (2009). They attempted to tackle the problem of multi-objective scheduling in repetitive construction and consider time and cost together.

The use of heuristic and meta-heuristic algorithms and other mathematical methods in the scheduling of repetitive construction projects is not limited to genetic algorithms. The neural network (Adeli and Karim, 1997), evolution strategies (Hsie et al., 2009), productivity scheduling method (Lucko, 2008) and object oriented scheduling (Fan and Tserng, 2006) are some examples.

It was mentioned earlier that the completion time is the subject of planning methods in the construction management literature. These planning methods are categorized into the activity-based planning approach and the workflow-based planning approach. The activity-based planning methods including network techniques, graphical techniques and operation research techniques were explained in this section and their limitations in the planning of repetitive construction were described. The next section explores the second category of planning and explains its origins and applications in construction planning.

2.3.2 Workflow-based planning approach

The early attempts of focusing on workflow rather than activities include the research undertaken by Birrell (1980) and Huang et al. (1992). This approach became more popular with the introduction of production planning to the construction industry (Koskela, 1992, Howell et al., 1993, Koskela, 1999, Koskela, 2000). Willenbrock (1998) suggested that the workflow-based planning view can be adopted in the house building industry and O’Brien et al. (2000) recommend that homebuilders who want to refine their existing field processes use workflow modelling.

O’Brien et al. (2000) divided homebuilders into four groups of small-volume, medium-volume, high-volume and production homebuilders. They reported that the construction process in the medium and high volume homebuilders is in-site and added that although production builders work in a factory-like environment, surprisingly they also follow the same construction process. In each of these three groups, the homebuilders use trades and subcontractors to implement each process and the product of one process is the raw material for the next one. Therefore, the workflow-based planning model would suit this system and would help homebuilders in these three categories.

The use of workflow-based planning approach in construction was further expanded under the name of “lean thinking” or “lean construction” which was an adaptation of “lean manufacturing”. According to Howell and Ballard (1998), lean construction views the entire project in production system terms whereas current construction project management views a project as a combination of activities. Two bodies, the International Group for Lean Construction (IGLC) and the Lean Construction Institute (LCI), have advocated the application of lean thinking to construction (Beary and Abdelhamid, 2005).

Conceiving the construction process as production, and the use of production operation management in construction, is not limited to planning and lean construction. Other attempts in this regard include just in time (JIT) (Akintoye, 1995, Pheng and Chuan, 2001, Kashiwagi and Slater, 2003), total quality management (TQM)(Rounds and Chi, 1985, Gilly et al., 1987, Burati et al., 1991, Rosenfeld et al., 1992, Culp et al., 1993, Deffenbaugh, 1993, O'Brien and

Fergusson, 1994, Shaida et al., 1999, Pheng and Teo, 2004), six sigma (Abdelhamid, 2003, Mohammed, 2005, Beary and Abdelhamid, 2005, Han et al., 2008), enterprise resource planning (ERP) techniques (Ahmed et al., 2003, Shi and Halpin, 2003, Cho et al., 2009) and supply chain management (SCM) (O'Brien, 1998, Vrijhoef and Koskela, 2000, Saad et al., 2002, Elfving, 2003, Jiang et al., 2003, Xue et al., 2005).

As mentioned above, workflow-based planning manages the flow of work within and in between work processes. With this view, the completion time (or cycle time as it is known in workflow-based planning) is influenced by workflow variability and reliability (Tommelein et al., 1999, Thomas et al., 2003, Sawhney et al., 2009, Machine et al., 2009), buffers (Howell et al., 1993, Thomas et al., 2004, Horman and Thomas, 2005) and work in process (González et al., 2009, Sacks and Partouche, 2009). Therefore, the workflow-based planning methods focus on these issues and use them to control and minimize the completion time. The following sections explain these parameters and cover the research, which investigated their impacts on construction process.

Workflow variability and reliability

Workflow variability damages the project performance through various causes (Tommelein et al., 2003, Alves and Tommelein, 2004). Variability in the flow of work can extend cycle time, reduce system throughput and increase the amount of waste in a process (Koskela, 1992). Construction labour performance can be improved using variability control and effective flow management (Thomas et al., 2003).

Construction projects inherently have a high level of variability. Therefore, managing variability is a crucial task for construction managers. To demonstrate the effect of workflow variability on the construction process, Tommelein et al. (1999) adopted a model of work in process transfer in a manufacturing line (so called “parade game”) suggested by Goldratt and Cox (1986). They argued that the parade game can be applied in the construction process as it represents the movement of trade contractors to work completed by a predecessor trade contractor. This research showed that the increase in variability leads to increased cycle time and higher level of work in process.

The research efforts on managing variability is a part of lean construction (Howell and Ballard, 1994, Ballard and Howell, 1998, Tommelein, 1998, Tommelein et al., 1999). Part of this research is the exploration of different planning methods aimed at maintaining workflow reliability. Workflow reliability has a profound impact on the work availability in the downstream process, and therefore, on the construction process performance (Tommelein, 2000). Abdelhamid et al. (2010) suggest that improving workflow reliability generates a more consistent, dependable and predictable flow.

Even flow production was proposed as a strategy for increase in workflow reliability and reduction of workflow variability (Ballard, 2001). This strategy can be implemented in two different ways: activity-based even flow, and start-based even flow. In activity-based even flow, the even workflow is maintained for each activity. Thus, there is a rigid schedule for activities and their related resources. In start-based even flow, only the first activity is scheduled and successor activities start as soon as predecessor activities are completed (Bashford et al., 2003). The simulation of construction of 90 homes by Bashford et al (2003) showed that the activity-based even flow strategy controls the variability and if the goal is to reduce management efforts and capture the even flow benefits, the activity-based strategy is the better choice.

Another method which was developed to shield downstream work from upstream variability, and relates directly to flow reliability, is the Last Planner technique (Ballard, 2000). In this technique, tasks are termed as “should-do”, “can-do” and “will-do”. The “should-do” tasks are derived from a master plan. The “can-do”s are indicated by the capacity of the related crew to implement the work, and “will-do”s are the ones that crews are actually committed to undertake. The reliability of planning is also measured by percent plan completed (PPC). The higher the PPC, the more reliable the planning (Koskela, 1999, Ballard, 2000, Beary and Abdelhamid, 2005, Cho et al., 2009, Kim and Ballard, 2010).

The use of buffers is another way to reduce variability and to increase workflow reliability. This is further explained in the following section.

Buffers

Buffers increase workflow reliability (Park and Pena-Mora, 2004), smooth workflow (Horman et al., 2003) and increase labour productivity (Horman and Thomas, 2005). They were proposed as effective tools for reducing the effect of workflow variability on downstream processes (Ballard and Howell, 1994). Since buffers are located between sub-processes, they minimize the interactions between them and prevent variation on a predecessor activity for transferring to successors and, therefore, resources can be used more efficiently (Howell et al., 1993).

The use of adequate buffers is suggested when there is a symbiotic relationship between construction crews. Research undertaken by Thomas et al. (2004) showed that the larger the buffer, the better the project performance. Sawhney et al. (2009) have investigated the impact of inspection buffers using the parade game. They concluded that the inspection buffers pass rate has a dramatic effect on workflow reliability, unless resources are unlimited.

Further, the level of workload in the buffers indicates the bottleneck activities. In production situations where activity production rates are not similar, the slowest activity with the lowest production rate dictates the production rate of the whole process. Therefore, the identification of this activity using buffers is essential for project and production management.

Although buffers play an important role in reducing workflow variability, they do not directly add value and, thus, they are wasteful (Goldratt and Cox, 1986, Womack and Jones, 1996, Hopp and Spearman, 2008). The reduction of buffers or inventories is one of the bases for just-in-time (JIT) management (Horman and Thomas, 2005). Sakamoto et al. (2002) argue that there is an optimum buffer size and there seems to be no advantage in large buffers.

This disadvantage is related to the higher level of work in process which is explained in the following section.

Work in process (WIP)

There is a significant difference in the project outcomes from WIP accumulation view versus WIP reduction view (Sacks and Partouche, 2009). The WIP accumulation hinders the production flow and contributes to increasingly longer construction duration. But due to the increase in the buffer size, the workflow variability decreases and project performance improves. On the other hand, WIP reduction increases productivity (Lieberman and Asaba, 1997) and at the same time increases the risk of the loss in workflow reliability. In either way, the effect of WIP on the process is substantial and needs to be carefully considered.

The effect of WIP on cycle time (or completion time as it is known in construction industry) can be explained using Little’s law. This law was proposed by John D. C. Little (Little, 1992) and holds for all production lines. Since this law is applicable in production lines with variability, it was suggested for the use in the construction production (Koskela, 1999).

Little’s law relates three parameters: cycle time, throughput and WIP. According to Little’s law the relationship between WIP, throughput (TH) and cycle time (CT) can be represented mathematically as follows (Hopp and Spearman, 2008):

$$WIP = CT * TH \qquad or \qquad CT = \frac{WIP}{TH} \qquad\qquad \textit{Equation 2-1}$$

As indicated by the above equations, reducing cycle time implies reducing WIP, provided throughput remains constant. However, there is a minimum cycle time in any production. This minimum cycle time is the result of the time needed for the processes and is influenced by the logic between sub-processes. Therefore, the above mentioned equation for the cycle time should be modified to:

$$CT = \begin{cases} CT_{\min} & if \quad WIP < WIP_0 \\ \frac{WIP}{TH} & Otherwise \end{cases} \qquad\qquad \textit{Equation 2-2}$$

In this equation, WIP_0 represents critical WIP. The critical WIP (WIP_0) is the WIP level for which a production line achieves maximum throughput with minimum cycle time. The following figure demonstrates the CT-WIP relationship in a production scenario.

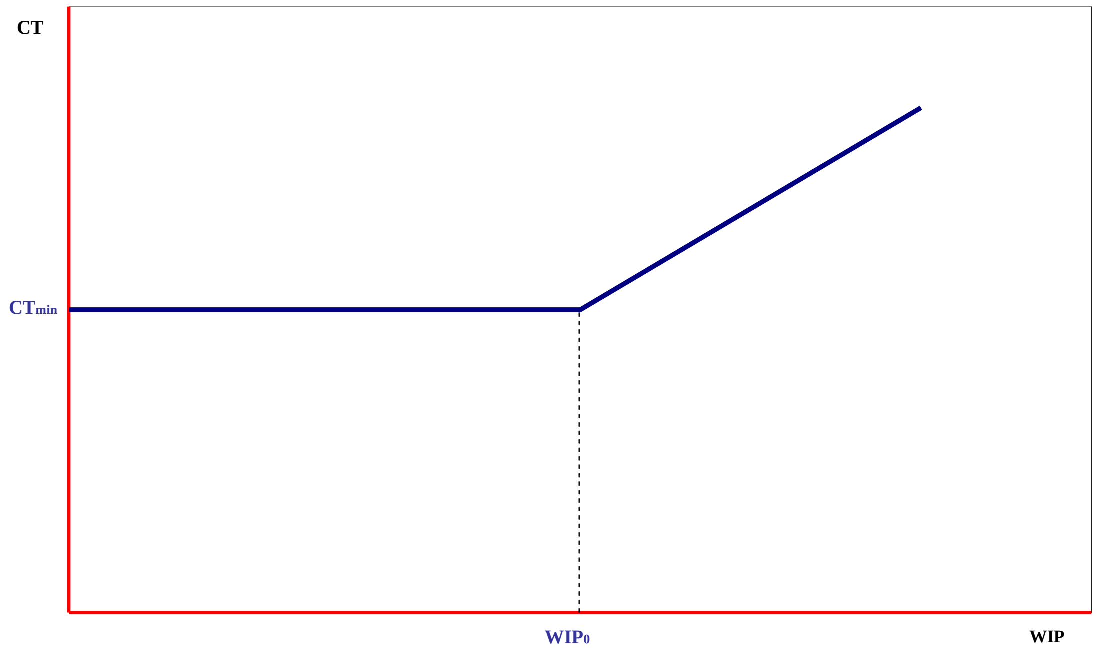


Figure 2-1 : WIP-CT relationship

As can be seen in this figure, WIP over the critical level makes the cycle time increase and WIP under the critical level returns the cycle times to a minimum level. Therefore, finding the critical WIP is an important issue for production managers. This level of workload is the optimum level for the WIP because at this level the throughput of production is also at the maximum level. Chapters five and six demonstrate a similar relationship between the number of houses under construction and average house completion time in the Australian house building industry and identify the critical WIP through data analysis.

Little's law assumes that the input and output rate of the process is constant, production is under steady-state condition and therefore, long production runs. Therefore, for normal construction productions which are temporary and affected by learning curves and environmental influences, Little's Law should be modified (Walsh et al., 2007).

The applicability of Little's Law in the residential production system was examined by Bashford et al (2005). They showed that the production variables such as work in process, cycle time and throughput are related and interconnected in this production. They conducted their research in the Phoenix, Arizona, housing market and concluded that the large variations in construction cycle time (completion time) can be explained by the changes in the production loading or WIP in this area. Building on Bashford et al.'s work, Chapter four investigates the recent increase in the average house completion time in Australia and explains the similarities between the trends for number of houses under construction and average house completion time in the house building industry.

The investigation of the implications of workflow-based planning in the house building industry, and particularly for house builders, cannot be examined in a real production building. The exploration of different production scenarios in a real production operation is extremely costly and, therefore, the modelling and simulation of real production is used for the purpose of this research. The next section explores the research which used simulation to build a foundation for the research design and further analysis.

2.3.3 Simulation

The aim of simulation modelling is to imitate the behaviour of a real system. While physical simulation of a construction process does not seem realistic, a computer simulation is proven to be efficient, cost-effective and inexpensive (Mao and Zhang, 2008). These computer simulations are used to learn how the real system works and focus on the study of the consequences of any changes on the system (Velarde et al., 2009).

The study of the system, and finding the relations between the activities, is the first step in simulation. The second step is to collect sufficient data that cover all the processes and products related to the system. In the third step, the objectives of the simulation are defined, as are the criteria, which will be used to interpret the results. Finally, appropriate software is used to develop the simulation model. This model can be used for the exploration of the effect of any changes in the system and the changes continue until the desired objectives are achieved (Abu Hammad et al., 2002, Kelton et al., 2010).

The use of simulation in construction industry began in the 1960s with simple network concepts. These network concepts were developed to study construction operation (AbouRizk et al., 1992). Cyclic Network modelling (CYCLONE) was one of the early modelling and simulation frameworks in the construction industry (Halpin, 1977). This framework consists of five modelling elements such as normal, combi, queue, function and counter (Palaniappan et al., 2006). CYCLONE could model and simulate repetitive and cyclic construction processes. This was followed by MicroCYCLONE which was software using a microcomputer (Lluch and Halpin, 1982). MicroCYCLONE is the most widely used system in academic research and is the basis for many construction specific simulation tools.

Ashley (1980) adopted the queuing model and simulated a repetitive project. This was based on the idea that repetitive units are organized in a queue to be served by an assigned crew. The objective of Ashley’s model was to minimize project duration and crews were scheduled to work on an activity as soon as possible. Kavanagh (1985) extended this model and included in the simulation the non-repetitive activities, the effect of the learning curve and weather impacts. This model was called SIREN (simulation of repetitive network) and was based on the queuing concept.

CYCLONE made the foundation for the development of many other simulation models and platforms including INSIGHT (Paulson, 1978), PROMAX (Dabbas, 1981), RESQUE (Chang, 1986), UM-CYCLONE (Ioannou, 1990), COOPS (Liu, 1991), CIPROS (Odeh, 1992), HSM (Sawhney and AbouRizk, 1995), PICCASO (Senior and Halpin, 1998) and SimCon (Chehayeb and AbouRizk, 1998).

Since there was a significant difference between simulation representation and real world construction, the applications of these models were mostly limited to the academic and research community. The process of developing and understanding simulation models was tedious for construction practitioners who have limited amount of time (Palaniappan et al., 2006). To overcome this difficulty, AbouRizk and Hajjar (1998) developed the concept of special purpose simulation (SPS) as an application framework for construction simulation tools.

SPS tools use familiar interfaces specialized to target a particular domain and require little or no simulation knowledge. The first tool, called AP2-Earth, allowed for the analysis of large earthmoving projects (Hajjar and AbouRizk, 1996). CRUISER was the second tool used for the modelling of aggregate production plants (Hajjar and AbouRizk, 1998). The third tool was CSD that was specialized for the optimization of construction site dewatering operations (Hajjar et al., 1998).

Simphony was founded on the experiences gained through the development of SPS tools. Simphony is an integrated environment for construction simulation. It significantly reduced the development time for new SPS tools due to the construction simulation object library provided within the framework (Hajjar and AbouRizk, 2002, Palaniappan et al., 2006). Simphony was applied for the simulation of production homebuilding (Sawhney et al., 2001) and the investigation of the effect of even-flow production in residential construction (Bashford et al., 2003). Sawhney et al. (2009) also used this platform to examine the impact of inspected buffers on production parameters in construction process.

Although the Simphony and SPS tools are designed for the construction processes, there is still research based on simulation modelling that uses general purpose simulation tools. Petri Net was used for the numerical simulation of the residential construction operation (Wakefield and Sears, 1997, Sawhney, 1997, Wakefield and O'Brien, 2004). Sacks and Partouche (2009) used ProModel discrete event simulation software and system dynamic was adopted for the simulation of the Last Planner (Mota et al., 2010).

Palaniappan et al.(2007) suggest that to model a generic construction process and capture the work flow characteristics, four constructs should be considered in the model. These constructs are: 1) Generating a set of work item per time period; 2) Computing the number of work items per time period at any downstream step; 3) Work in Process; and 4) Number of work items waiting for a resource. This research uses these constructs and adds more components to the model to suit the workflow modelling of house building operations. The detailed explanation of the modelling and simulation can be found in chapter seven.

2.4 Chapter summary

This chapter explored the literature about research related to house completion time and established an understanding of this parameter. Since the focus of the research is on house completion time the housing literature was investigated. It was shown that because of three reasons, completion time is not sufficiently addressed in this part of literature.

First, the focus of housing literature is on the demand side of the housing market rather than supply, and house completion time is related to housing supply. Second, the housing supply literature is concerned with the effective factors on the supply and price or cost elasticity. This research rarely investigates the quality of supply, including the completion time. Third, housing supply usually is represented by the number of housing starts, while the completion time is related to housing completions.

Further, the construction management literature was explored in regard to completion time. It was explained that completion time is the subject of construction planning research and thus, the planning approaches were investigated. The first category of planning was activity-based planning approach which includes network scheduling techniques, graphical scheduling techniques and operation research techniques. With this approach, construction projects are considered as a connected network of activities, and therefore, they can be successfully managed by implementation of set of management tools on the individual activities. According to this approach, the changes in house completion time can be explained with the changes in the activities.

The second category of planning approach was workflow-based planning. This planning approach considers construction projects as a series of work processes and places an equal emphasis on the work processes as well as their connections. According to this approach, project managers are required to manage flow of work between these processes and within them. The completion time is, therefore, related to workflow and its influencing factors should be found between the workflow parameters. These parameters were explained in this chapter and included workflow variability and reliability, buffers and work in process.

The investigation of house completion time using workflow-based planning approach needs to be undertaken using modelling of an actual house building process and simulation of different scenarios. Therefore, the simulation methods and their applications in construction management were also explained in this chapter.

The next chapter uses the planning approaches mentioned in this chapter and demonstrates the research design adopted for this research.

3 CHAPTER THREE - RESEARCH DESIGN

3.1 Introduction

The previous chapters explained the current situation of house completion time in Australia and explored the existing knowledge about this parameter. This exploration led to an understanding of different theories on influencing factors on house completion time and two planning approaches were distinguished and chosen as potential approaches for explanation of changes in this parameter.

However, before the investigation of completion time using these planning approaches begins, the research aim and objectives need to be clarified. This chapter commences with this clarification and continues with research design. The research design covers the issues around research philosophy, strategy of inquiry and research method. The rationale behind the research design is explained further in the chapter and the details of research method are described. These details include definitions, data collection and case study selection.

The following section is devoted to the clarification of research aim and objectives.

3.2 Research aim and objectives

The main aim of the research is to investigate house completion time in Australia using the workflow planning approach. In order to reach this aim, there are objectives that needed to be achieved. The following paragraphs describe these objectives.

The changes in completion time can be explained using two construction project planning approaches. The activity-based planning approach suggests changes in the scope of work and production rate as possible reasons for changes in completion time, and workflow-based planning approach proposes the number of houses under construction as the possible reason.

Although the activity-based planning approach is extensively criticized in the literature for its limitations in addressing the issues related to house completion time, this research attempts to add to these efforts and confirm this shortcoming in the explanation of changes in completion time in the Australian house building industry. The potency of the workflow-based planning approach is also discussed in the literature and this research confirms it by showing the potentials in the workflow-based planning approach in explaining changes in completion time.

Workflow-based planning approach suggests that since there is a relationship between cycle time, work in process and throughput in production operations, there might be the same kind of relationship between house completion time, number of houses under construction and number of house completions. Therefore, one objective of the research is to investigate this relationship using the data from different cases and adapt the relationship applied in production planning for the use in the house building industry.

According to the workflow-based planning approach, house completion time extends beyond its minimum level when the industry is working over its capacity and the housing market is in under supply. On the other hand, when industry works under its capacity and there is an over supply in the market, the completion time stands at the minimum level. Therefore, the next step is to explore this implication of the workflow-based planning approach and identify capacity of the house building industry, and to propose the completion time as an indicator of the state of housing supply.

So far, the investigation of completion time in the house building industry, the applicability of the workflow-based planning approach, and the implications of this approach at the industry level, are covered in the objectives. However, the workflow-based planning approach has implications at company level for the individual house builders. To explore these implications, one needs to model an actual house building process and simulate different operation scenarios using this model. Thus, the next part of the research needed to be devoted to the data gathering of an actual house building process and development of a workflow model.

The exploration of the implications of the workflow-based planning approach for house builders leads to the investigation of the effect of different operational strategies on the completion time. This research considers the consequences of two common practices in house building operations on the completion time using the workflow-based planning approach.

In the house building companies, construction commencement is usually decided by the people outside the construction process, such as marketing staff. This research sheds light on the importance of this decision by simulating different scenarios of construction commencement intervals and showing their effects on the completion time and other production parameters. The second practice is the existence of different house design options in one house building operation. The investigation of the consequences of this practice on the completion time is the final objective of this research.

The following statements summarize the research aim and objectives:

Research aim is to investigate house completion time in Australia using the workflow planning approach.

Research objectives are:

- To confirm the shortcomings of activity-based planning approach and the potency of workflow-based planning approach in explanation of changes in average house completion time

- To investigate the relationship between average house completion time, number of houses under construction and number of house completions

- To explore the implications of this relationship in the introduction of average house completion time as an indicator of industry's capacity

- To establish a workflow planning model that describes the house building process at company level

- To explore the implications of workflow planning in finding the effect of commencement intervals and house design variation on completion time

The next section provides the research design and the rationale behind the design selection.

3.3 Research design

In the previous section, the research aim and objectives were discussed. This section attempts to provide a plan or a framework for the research. This plan spans the decisions from broad assumptions to detailed methods of data collection and analysis (Creswell, 2009).

The discussions over research design covers a broad area of philosophical foundations of research, ontology, epistemology, theoretical research perspectives, methodology and methods (Blaikie, 1993, Creswell, 2009, Crotty, 1998). However, there is no common research framework or even a consistent terminology in the literature in this regard. Further, most research methods literature is aimed at social science studies or qualitative methodologies. Literature on quantitative research is scarce and often the need for explanation of philosophical worldviews behind different methodologies and methods is ignored.

This research, however, applies the framework proposed by Creswell (2009) to address all the issues related to its design. This framework consists of three elements, namely, philosophical worldview, strategy of inquiry, and research method. Figure 3-1 illustrates this framework and following sections explain how it is adopted to this research.

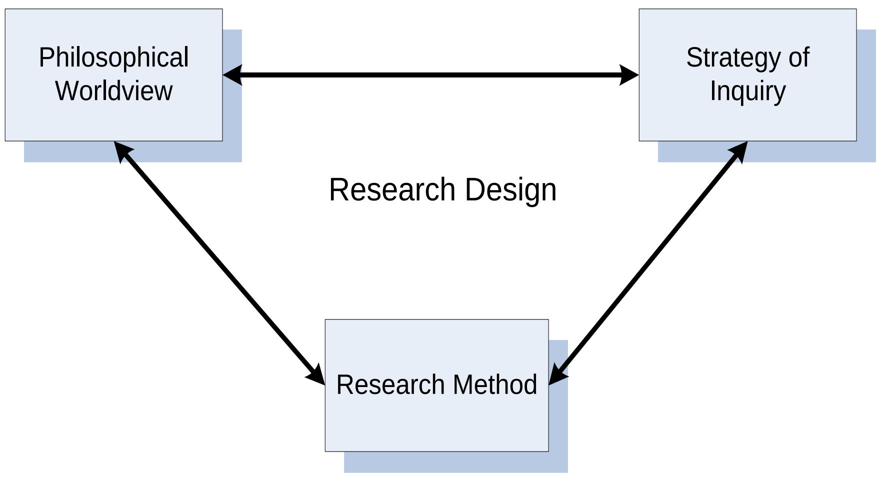


Figure 3-1: Research Design Framework (Creswell, 2009)

3.3.1 Philosophical worldview

Although philosophical ideas usually remain hidden in research, they influence its practice (Slife and Williams, 1995), and failure to understand them can affect the quality of the research (Easterby-Smith et al., 2002). The term *worldview* is adopted in this research from Creswell (2009) and means a basic set of beliefs that guide action. The same concept was termed by Crotty (1998) and Blaikie (1993) as epistemologies and ontologies.

Creswell (2009) classifies research philosophical worldviews as *postpositivist*, *social constructionist*, *advocacy and participatory*, and *pragmatic*. The major elements of each of these are presented in table 3-1.

Table 3-1: The elements of four philosophical worldviews

Postpositivism	Constructionism
• Determination • Reductionism • Empirical observation and measurement • Theory verification	• Understanding • Multiple participant meanings and social and historical construction • Theory generation
Advocacy/Participatory	**Pragmatism**
• Political • Empowerment issue-oriented • Collaborative • Change-oriented	• Consequences of actions • Problem-centred • Pluralistic • Real-world practice oriented

According to Creswell (2009), "postpositivist assumptions have represented the traditional form of research, and these assumptions hold true more for quantitative research". "Postpositivists hold a deterministic philosophy in which causes probably determine effects or outcomes". "It is also reductionistic in that the intent is to reduce the ideas into small, discrete sets of ideas to test, such as the variables that comprise hypotheses and research questions. The knowledge that develops through a postpositivist lens is based on careful observation and measurement of the objective reality that exists out there in the world". In a postpositivist approach, the researcher "begins with a theory, collects data and either supports or refutes the theory, and then makes necessary revisions before additional tests are made".

It was mentioned in the research objectives that two planning approaches are examined in this research to find the reasons for changes in the average house completion time. A deterministic approach is employed; the variables related to house completion times are measured and numerical. The objectives include the propositions that are derived from theories and it is explained in the following sections that this research is designed to refute, support or revise these propositions and theories. In addition, the mode of inquiry is quantitative (Bryman, 1984). Thus, this research philosophical worldview falls in the postpositivist category.

Epistemology is a theory of knowledge and concern about what is considered as acceptable knowledge in a particular discipline (Blaikie, 1993, Bahari, 2010, Bryman, 2004). Postpositivism views reality as universal, objective and quantifiable. From this perspective, reality is the same for everyone and through the application of science, this shared reality can be identified and seen (Darlaston-Jones, 2007). The epistemological root for this is *objectivism*. "*Objectivist epistemology* holds that meaning, and therefore, meaningful reality, exists as such apart from the operation of any consciousness (Crotty, 1998)".

Thus, this research identifies itself with an objectivist epistemological position. This research looks for an objective truth about the relationships between the house building industry variables. The researcher's conscience is apart from the research and therefore, anyone can undertake the same approach and reach the same conclusions.

Ontology is parallel to epistemology and a part of philosophical worldview. Ontology is the science or study of being (Blaikie, 1993). In ontology, realism sustains that reality exists outside the mind (Crotty, 1998, Chevez, 2009, Krauss, 2005). This research takes realism as its ontology, because it is conducted in the way that the world exists independently from our consciousness.

3.3.2 Research strategy of inquiry

The second element in the research design is the strategy of inquiry; refer to figure 3-2. A piece of research can be classified from the strategy of inquiry as qualitative and quantitative (Kumar, 2005).

"Qualitative research is a means for exploring and understanding the meaning individuals or groups ascribe to a social or human problem"." Those who engage in this mode of inquiry support a way of looking at research that honours an inductive style, a focus on individual meaning and the importance of rendering the complexity of a situation" (Creswell, 2009). Qualitative research explores the subject without prior formulations. "The object is to gain understanding and collect information and data such that theories will emerge. Thus, qualitative research is a precursor to quantitative research" (Fellows and Liu, 2008).

“Quantitative approach (inquiry) tends to relate to positivism and seek to gather factual data, to study relationships between facts and how such facts and relationships accord with theories and findings of any research executed previously (literature). Scientific techniques are used to obtain measurements – quantified data. Analysis of the data yield quantified results and conclusions derived from evaluation of the result in the light of the theory and literature” (Fellows and Liu, 2008).

As explained before, this research is undertaken with a postpositivist worldview. The data used in the analysis are factual data. These data include average house completion time, average house floor area, number of house completions and number of houses under construction, and are derived from time series reported by the Australian Bureau of Statistics (ABS), which are collected scientifically. The objectives of the research are the investigation of the relationships between these parameters and propositions about the possible relationships are derived from the existing knowledge (literature). Thus, the research strategy of the inquiry, by definition, is quantitative.

However, strategy of inquiry is not only a decision about quantitative or qualitative research, but also the type of study that a researcher wants to pursue (Creswell, 2009). These strategies are also known as research methodologies or research styles (Fellows and Liu, 2008) and research approaches (Bell, 2005).

Crotty (1998) lists these strategies as experimental, survey, ethnography, phenomenological, grounded theory, heuristic inquiry, action research, discourse analysis and feminist standpoint research. Bell (2005) names action, ethnography, survey, case study and experimental as research strategies and Yin (2009) suggests that there are five common research strategies: survey, experiment, archival analysis, histories and case studies.

The selection of the best research strategy depends on the type of research question (what, how, why, etc.), the degree of control over actual events and whether the focus of research is on past or current events (Yin, 2009). Table 3-2 shows how these three conditions relate to different research strategies.

According to (Yin, 2009), the first indicator for the appropriate research strategy depends on the research question. “What” questions are usually exploratory. These questions need survey or archival analysis to find the answers. The main question of this research is not a “what” question and thus it is not exploratory. Therefore, survey and archival analysis cannot be proper strategies for this research.

Table 3-2 :Research strategies of inquiry (Yin, 2009)

Strategy	Form of research question	Require control of events	Focuses on contemporary events
Experiment	How, why?	Yes	Yes
Survey	Who, what, where, how many, how much?	No	Yes
Archival analysis	Who, what, where, how many, how much?	No	Yes/no
History	How, why?	No	No
Case study	How, why?	No	No

The three other strategies answer “how” and “why” questions, which are similar to the objectives of this research. The second condition for research strategy selection is the level of control of events. Experiment needs a full control on the event, whereas history and case study do not need this. None of the variables studied in this research is the under control of the researcher. The average house completion time, average house floor area, number of house completions and number of houses under construction are parameters used in this research and all of them are related to the house building industry. Thus, an experimental approach is not an adequate strategy.

The third condition is the focus on contemporary events. This is the condition that separates history from case study research (table 3-2). The case study research is often undertaken on contemporary events while history research is on past events. Considering this condition, this research, which focuses on recent changes in the house building industry and tries to predict its future should be undertaken using a case study approach.

Case study research is often suggested as a strategy in undertaking qualitative research. However, Yin (2009) argues that case study can be used in quantitative research too. Gillham (2008) takes a similar approach. He argues that case study research is quantitative when it tests a hypothesis, is objective and demonstrates the changes that have occurred.

All these demonstrate that *quantitative case study strategy/methodology* is appropriate for this research and, therefore, was applied in its implementation. The next section explains the case study research design.

Case study research design

So far, the philosophical worldview of the research and the strategy of inquiry were explained. It was shown that quantitative case study research is the strategy that best describes this research. However, knowing the strategy is not enough to carry out the research. This section clarifies the details of this strategy and design.

Single-case or multiple-case design: A primary step in case study design is deciding between a single case and multiple cases strategy. These two designs are differentiated according to the research goal *(Gerring, 2007)*. Research might be oriented toward hypothesis generating or hypothesis testing. It might be concerned about causal mechanisms and causal effects. External or interval validity might be prioritized and scope of the causal inference might be deep or broad *(Gerring, 2007)*. All these factors characterize case study research and indicate whether it should follow a single-case study design or multiple-case study design. Table 3-3 clarifies these considerations.

Table 3-3: Research goals of single case study and multiple case study approach

Research goal	Single case study	Multiple case studies
1. hypothesis	Generating	Testing
2. validity	Internal	External
3. causal insight	Mechanisms	Effects
4. scope of proposition	Deep	Broad

Yin (2009) suggests that there are five reasons to undertake a single-case study design. This design is used when it represents a *critical case* in testing well formulated theory. In this situation, the theory specifies a clear set of propositions and the circumstances in which the proposition are believed to be true. Single-case is also done when there is an *extreme* or a *unique case*. Further, when case study is the *representative* or *typical case*, single-case study is a suitable design. In this case, the objective is to capture the circumstances and conditions of a commonplace. The *revelatory* case and the *longitudinal* case are two other rationales for single case study design (Yin, 2009).

The use of multiple-case study is impossible where there is a critical, unique or revelatory case. However, the main rationale for choosing multiple-case study is the logical link between the data analysis and research objectives. The multiple-case study is undertaken when *replication* is used. In this design, each case either predicts similar results (a literal replication) or predicts contrasting results but for anticipated reason (a theoretical replication) (Yin, 2009).

Therefore, the decisive points between single-case study and multiple-case study are hypothesis, validity, causal insight, scope of proposition, nature of the research and replication. The following sections examine these criteria against the objectives of the research and explain which case study design is selected for these objectives.

Research goal; hypothesis: The case study design can be used for generating or testing of a theory. In this research, the first three objectives consist of propositions about the possible reasons for changes in the house completion time and the relationship between house completion time, number of houses under construction and number of house completions. These propositions are derived from theories well documented in the literature (chapter three). Activity-based planning and workflow-based planning approaches are the foundation for these propositions. Thus, according to table 3-3, a multiple case study design is appropriate for the investigation of the validity of these propositions.

The last two objectives need a different design. These objectives attempt to clarify what happens when the construction commencement interval is reduced in a house building operation. The variation in house type design is another operational strategy and this research investigates its consequences. Therefore, a single case study is applied for this part of research.

Research goal; validity: The multiple-case study is always a better representation of the whole population of interest and, therefore, seeks external validity. On the other hand, single-case study designs rely on internal validity (Gerring, 2007, Woodside, 2010).

In this research, the first three objectives are concerned with the house building industry and all the analyses are on the industry level. Therefore, the case studies are different house building industries in the country. They include house building industries in the five largest states of Australia. These states cover more than 95 percent of the country's population. The details of these cases are described in following sections. In addition to these five cases, a meta case is introduced to the study that sums up all these state cases. This case is the whole Australian house building industry that covers all states included in the study and the rest of the country. Since the whole population is covered in this part of research, the multiple-case study is externally valid.

The research objectives that are investigating the implications of the workflow-based planning approach at the company level, possesses a different rationale. In this part, one case of a house building operation is considered. In this case, all the details, elements and rationale between sub-processes are studied. This case is used to clarify the consequences of some operational strategies in a house building operation. It is shown that the consequences are connected to the strategies and the relationship between different operational parameters is clarified. Therefore, as Yin (2009) suggests, this part of research has internal validity and single-case study is a proper design for it.

Research goal; causal insight: According to two previous criteria, the objectives related to the industry needed to be addressed using multiple-case study research and the objectives at company level using single-case study. The causal insight is another criterion that strengthens this argument. According to Table 3-3, the causal insight is divided into causal mechanisms and causal effects. The causal effect refers to the magnitude of a causal relationship and the relative precision or uncertainty of that point estimate (Gerring, 2007). The causal mechanism is more concerned with the connection between cause and effect. For this kind of study, a multiple-case study approach cannot help. Instead, a single case study including all the details of the relationship between cause and effect can be insightful.

In this research, the first three objectives show the possible relationships between house completion time in Australia and average house floor area, number of house completions and number of houses under construction. This part of research is at industry level and at this level, it is difficult to investigate the precise detail of the industry and find the exact connection between the cause and effect. Therefore, the multiple case study design that was suggested by previous criteria for this part of research is confirmed as also appropriate for establishing causal insight.

On the other hand, that part of the research focused on the actual house building process investigates all the details, including the resources, activities and their relationships and other influencing factors on completion time. In this part, the causes of changes in house completion time are the operational strategies, which are predetermined by the researcher. The mechanism between cause and effect is shown in this part of research to help practitioners understand the process and implement a proper operational strategy. Thus, single-case study with a mechanism of causal insight is appropriate for this part.

Research goal; scope of propositions: According to Table 3-3, case studies are divided into broad and deep, based on their scope of propositions. This criterion also recognizes the need for different case study design for different parts of the research. The industry-focused area of the research tackles the issues related to the changes of completion time in a broad context and, therefore, the multiple-case study approach is considered appropriate for this part.

The part of the research at company level follows a different approach and goes to the detail of the house building operation to find out what can be done to improve the existing operations, with minimum cost, using changes in the operational strategies. Thus, this part is undertaken using the single-case study approach.

Nature of the research: Single case study is suggested for research on critical, unique, typical, revelatory or longitudinal cases. It was shown in the previous section that a single-case study is suitable to address the last two research objectives. This case study is a typical house building operation and, therefore, complies with the nature of research indicated for the single-case study.

Replication: According to replication logic, the previously developed theory is used as a template to compare the results of the cases. Each case is subjected to the template individually, and the fit of data noted for confirmation, rejection or further refinement. The multiple-case study is weak when there is not a theoretical template (Blismas, 2001). This logic is used in the analysis of the house building industry where a set of propositions is offered by planning approaches. Each case is tested against these propositions and then becomes a rejecting, confirming or refining case.

3.3.3 Research method

The third element in the research design framework is research method; refer to Figure 3-2. This element describes the methods for data collection, analysis and interpretation of the results (Creswell, 2009). It was explained in the case study design that this research uses two case study approaches. The multiple-case study approach is the appropriate design for research on the objectives related to the house building industry, and single-case study for the objectives related to the house building operation at the company level. Therefore, these two different designs are treated differently for their research method.

Research method for the multiple-case study

The following explains the definitions used in the research, data collection, research method logic and case study selections.

Definitions and data collection: The data needed for this study include average house completion time, number of house completions, average house floor area and number of houses under construction. The reasons for the use of this set of data are explained before each data analysis in chapters four to six. This section defines them and explains the issues around data gathering.

House:

A house in this study is a separate house "which stands alone in its own grounds separated from other dwellings by at least half a meter". This house is "predominantly used for long-term residential purposes and consisting of only one dwelling unit." (Australian Bureau of Statistics, 2006b)

Commencement

"A building is *commenced* when the first physical building activity has been performed on site in the form of materials fixed in place and/or labour expended (this includes site preparation but excludes delivery of building materials, the drawing of plans and specifications and the construction of non-building infrastructures, such as roads)" (Australian Bureau of Statistics, 2006b)

Completion

"A building is completed when building activity has progressed to the stage where the building can fulfil its intended function" (Australian Bureau of Statistics, 2006b).

Average house completion time

The first set of data at the core of this research is average house completion time. This data is used as the representative of house completion time in Australia and is defined as "the quarterly estimates of the average time taken to build new houses".

"These data are compiled from the Australian Bureau of Statistics (ABS) quarterly Building Activity Survey, analysing the commencement and completion quarters for new houses". "Houses taking more than three years to complete, being in the most extreme 1% by value or being constructed in groups of 10 or more are excluded. This excludes approximately 2.5% of completed houses".

Considering the commencement and completion definitions, average house completion time is the time between the first physical building activity and readiness of the building for occupation. This definition helps this study specifically focus on the house building industry. The approval process and the activities before the start, and after finish, of the construction process are excluded.

Average house floor area

"The *floor area* of a building is a measure of the amount of useable space in a building (and its attachments) at the final stage of its construction and is measured in square metres. The boundary of the recorded floor area of a building is delineated by the external perimeter of the exterior walls of the building" (Australian Bureau of Statistics, 2006b). The average floor area is reported by ABS in general for new residential buildings and in particular for new *houses,* and is used in this research as *average house floor area* (Australian Bureau of Statistics, 2010c).

Number of house completions

The *number of house completions* is the number of houses *completed* in one quarter and is collected by ABS at the end of each quarter. This includes all the new *houses* in that quarter including the *houses* built by private sector and public sector.

Number of houses under construction

"A building is regarded as being *under construction* at the end of a period if it has been commenced but has not been completed, and work on it has not been abandoned". ABS reports *the number of houses under construction* quarterly. These data include the houses built by private and public sectors and covers the whole house building industry.

Research logic: Replication is the logic connecting the analysis to the research objectives. Each part of analysis starts with a proposition. The proposition is tested against all case studies and the results are the rejection, confirmation or refinement of the proposition. Statistical and mathematical tools are employed in the data analysis and theory testing. The final result of the multiple case studies is a rejected proposition along with a fine proposition which has been confirmed and refined by the cases.

Case study selection: The cases in this part of research are specified as house building industries. This industry could be in a local area, a city, a state or the whole country. One requirement for the workflow analysis is that each case study is assumed to work like a production system. This production system has a limited number of resources and works like a closed system. Therefore, the industry case should be selected to fulfil this requirement.

Population map of Australia indicates that most of the population is concentrated in and around states capital cities (figure 3-2). The capital cities are hundreds or thousands of kilometres from each other and population is scarce close to the state borders. The extreme case is Western Australia where the centre of population in Perth is more than two thousand kilometres from the closest capital city which is Adelaide. In house building where employment is dominated by sub-contracting, although there are companies which have expanded interstate, the actual work is done by the local resources in the state. Therefore, the house building industry in each state works similar to a closed system with limited resources inside the state. This makes the state division of industry an appropriate base for selection of case studies.

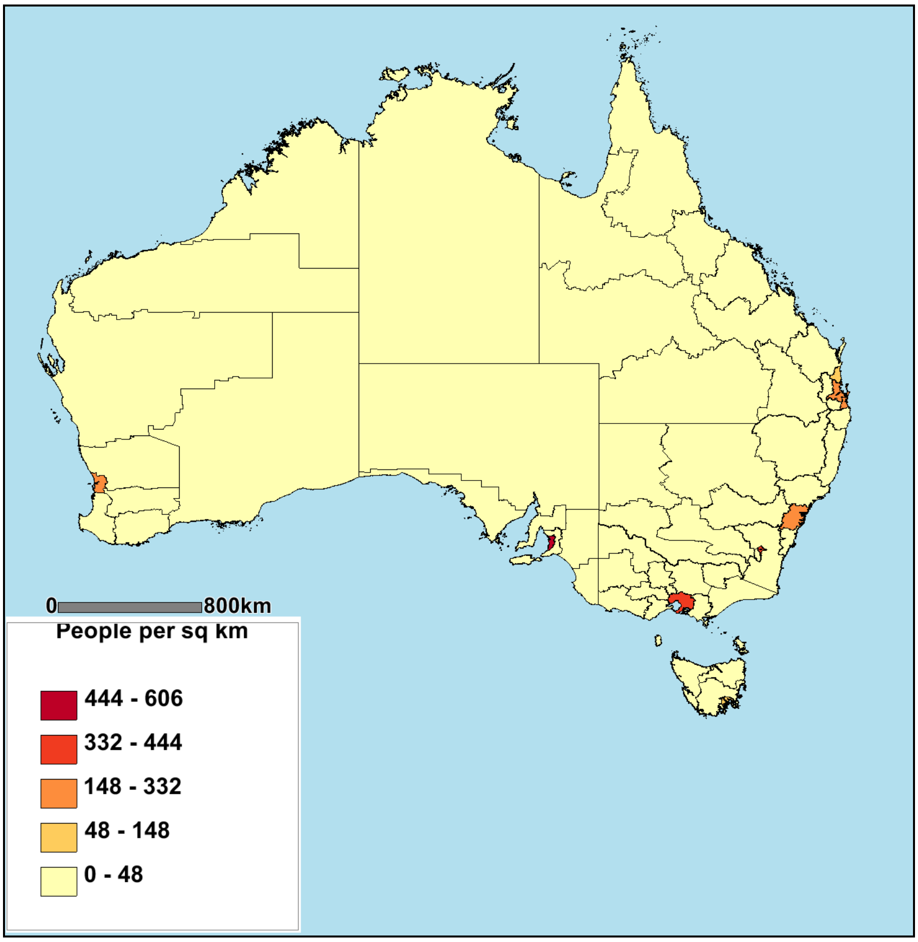


Figure 3-2: Australia population density map (number of people per square kilometre)

Another criterion for the selection of case studies is availability of data. The ABS provides data according to the state divisions, and thus the data needed for this research are available for each state separately. Therefore, the researching of the industries in different States is possible.

Five of the most populous states in Australia are selected as case studies. These cases are New South Wales, Victoria, Queensland, Western Australia and South Australia. They contain 95 percent of country's population. However, to be able to generalize the result for the whole country, the country is considered as a meta case that sums up all the state cases and the remaining parts of the country. Since Australia is a country surrounded by water, this meta case works like a closed system and its house building industry is an appropriate case for this research.

The following sections are introductions to the five State case studies.

- **New South Wales (NSW)**

NSW is located in southeast of the country and its neighbouring States are Victoria, South Australia and Queensland. The State area is 809,444km^2 and it is the fourth largest State in the country. However, NSW contains 33.1 percent of Australia's population with population of 7,238,819 people and it is the most populous State in the Country.

According to NHSC estimation, the housing supply shortage has reached 65,100 in 2010 and it will reach 168,800 by 2010 in this State(National Housing Supply Council, 2010b). The same report projects the dwelling completion 2020 will be 32,900 dwellings. This shows the demand-supply gap is a serious issue in this State.

Among all kinds of dwellings, the detached houses make up seventy one percent in the State. The house building industry in this State has completed on average 20,754 houses in the period of year 1999 to 2008 (Australian Bureau of Statistics, 2010b) and top 20 home builders market share in 2009/2010 was 20 percent (Housing Industry Association, 2010a).

The capital city of the State is Sydney and, by the end of 2006, 62.9 percent of the State's population were living in this city. The travelling distance between Sydney and Victoria's Capital city (Melbourne) is 880 km, between Sydney and South Australia Capital city (Adelaide) is 1,409 km, and between Sydney and Queensland Capital city (Brisbane) is 934 km. As can be seen in Figure 3-3, the population is centralised at capital city and because of the long distances between population centres, movement of resources is difficult and most of the human resources are local.

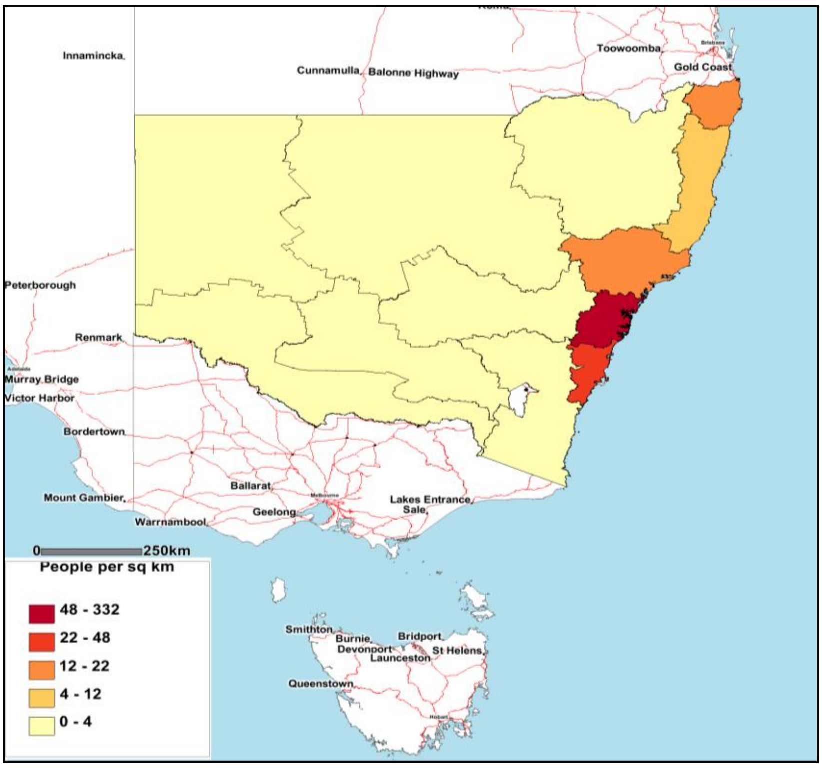


Figure 3-3: New South Wales population density

• **Victoria (Vic)**

Victoria with the area of 237,629 km2 is the smallest mainland state. However, it is the second most populous State in the country. The population of State was 5,547,500 people in 2010 with seventy-five percent living in Melbourne, the capital city (Australian Bureau of Statistics, 2010a).

Victoria borders NSW in the north and South Australia in the west. The closest capital city to Melbourne is Adelaide in South Australia with travelling distance of 728 km. As mentioned earlier, the distance between Melbourne and Sydney is 880 km.

The housing supply shortage has been also reported by NHSC for this State. The shortage estimation for 2010 was 25,000 and was predicted to reach 32,500 dwellings by 2020 (National Housing Supply Council, 2010b). Similar to NSW, the detached houses are the dominant type of dwelling in this state and make seventy-seven percent of all dwellings (Australian Bureau of Statistics, 2006c). The house building industry has built 30,000 houses per year on average during past ten years and the market share of top 20 homebuilders in this state was 32 percent in 2009/2010 (Housing Industry Association, 2010a).

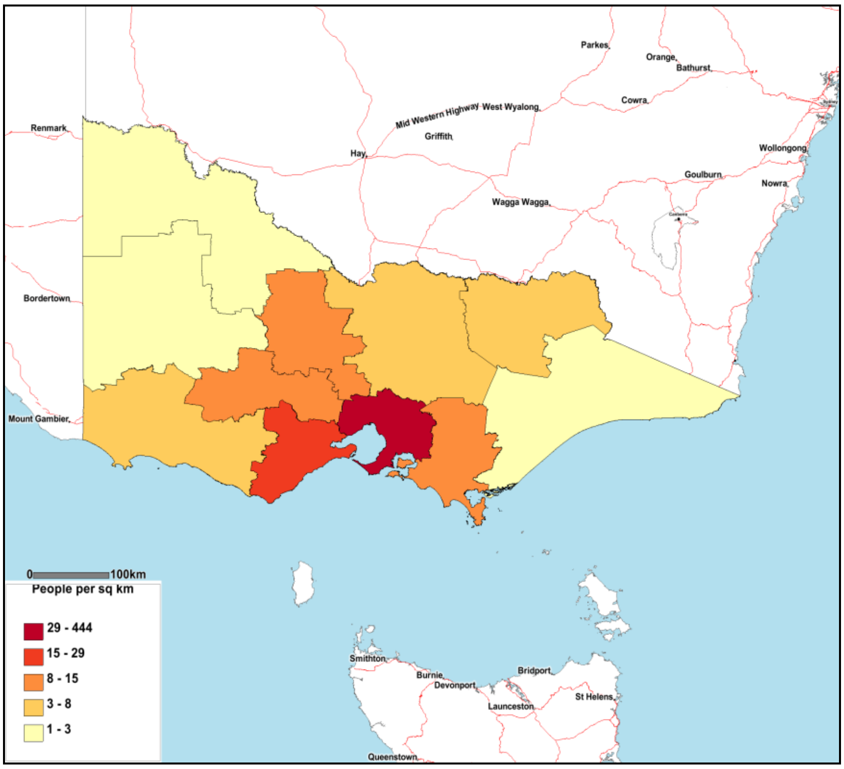


Figure 3-4: Victoria population density

• **Queensland (Qld)**

Queensland is the second largest State by area and the third most populous State in the country. It borders New South Wales to the south, Northern Territory to the west and South Australia to the South West. The population of State at the end of 2010 was 4,516,400. The State's area is 1,852,642km^2 (Australian Bureau of Statistics, 2010a).

Housing supply shortage in Queensland is the second worst in the country. According to NHSC, this shortage in 2010 was 61,900 and it will reach 135,400 dwellings by 2020. The number of dwelling completions was also projected to reach 40,300 dwellings (National Housing Supply Council, 2010b). This shows the current trend of dwelling completions does not meet the demand and the demand-supply gap is expected to widen in the next ten years.

About eighty percent of all dwellings in this State are detached houses (Australian Bureau of Statistics, 2006a). The output of the house building industry in past ten years was on average 24,000 houses (Australian Bureau of Statistics, 2010b) and the market share of top 20 homebuilders was 24 percent in this State in 2009/2010(Housing Industry Association, 2010a).

As can be seen in Figure 3-5, the majority of population in this State is centralised around South East area. Brisbane, the State capital city, is located in this area and contains 45 percent of the State's population. The closest capital city to Brisbane is Sydney with 934km distance.

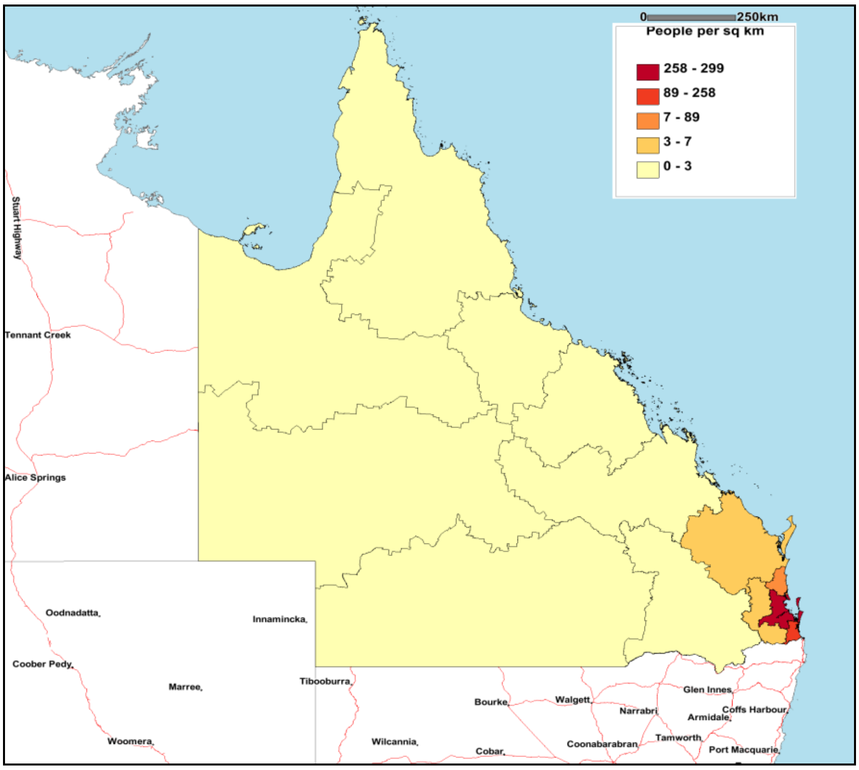


Figure 3-5: Queensland population density

• **Western Australia**

Western Australia is the largest State of the country. It covers one third of Australia and borders South Australia and Northern Territory to the east. The area of the state is 2,645,615km^2, which is larger than many countries in the world. In terms of population, this State is the fourth most populous state in the country. According to Australian Bureau of Statistics, the State's population is 2,236,900 people of which eighty-five percent live in south-west corner of the State (2010a). Figure 3-6 demonstrates the population density of the State. Perth is the capital city containing seventy-five percent of the State's population. The closest capital city to Perth is Adelaide with 2,700km distance. This adds to the remoteness of the State and the locality of the house building resources.

Western Australia is also facing a shortage in housing supply. This shortage in 2010 was 34,700 dwellings and was predicted to reach 69,500 dwellings by 2020 (National Housing Supply Council, 2010b). Similar to previous States, detached houses are the dominant type of dwellings in this state, and according to census 2006, about eighty-one percent of all dwellings in the State were detached houses. The house building industry in this State built about 16,700 houses per year during 1999 to 2008 (Australian Bureau of Statistics, 2010b). The structure of the house building industry in this State is somehow unique. The market share of top 20 homebuilders in this state is seventy percent and from this, sixty-four percent of the market belongs to top 10 homebuilders (Housing Industry Association, 2010a).

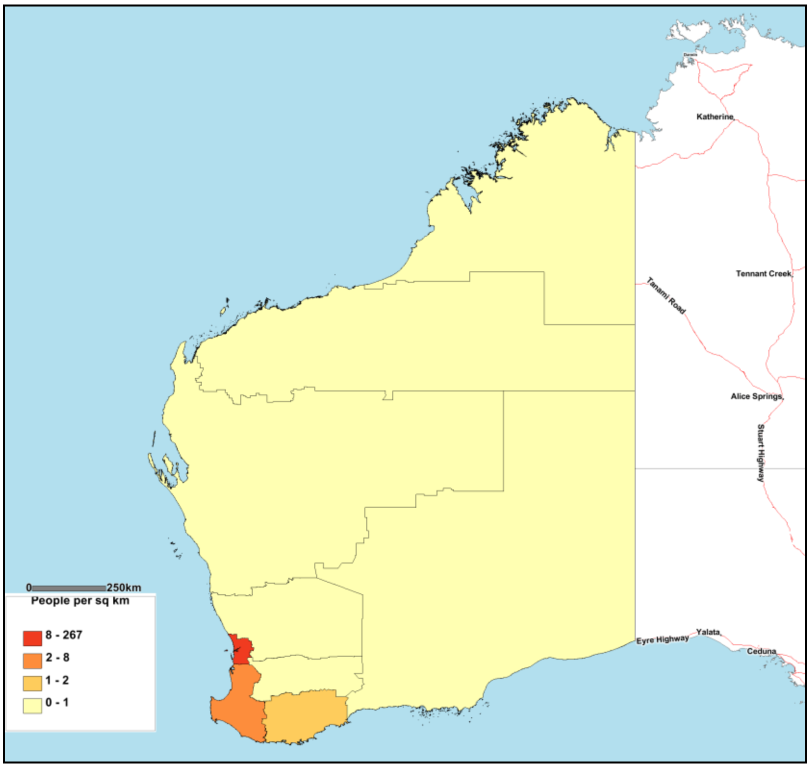


Figure 3-6: Western Australia population density

- **South Australia**

South Australia is the fifth case study in the research. This State is the fifth most populous and fourth largest State in Australia. The State's area is 1,043,514 km2 and its population in 2006 was 1,622,700 people (Australian Bureau of Statistics, 2010a). The capital city of the State is Adelaide with population of 1,187,456 people. As these data show, the majority of population of the State live in the capital city and the rest of the population is more centralised along the coastline in the southern parts of the State (Figure 3-7).

Housing supply shortage in South Australia, according to NHSC (2010b), was 1,800 in 2010. However, the gap between housing supply and demand is expected to widen in the next ten years and the housing shortage will reach 19,500 dwellings. Eighty percent of dwellings in this

State are detached houses and the house building industry has built about 7,670 houses per year during past decade (Australian Bureau of Statistics, 2010b, Australian Bureau of Statistics, 2006a). The market share of top 15 homebuilders, which build more than fifty dwellings per year, is thirty-eight percent in this State (Housing Industry Association, 2010a).

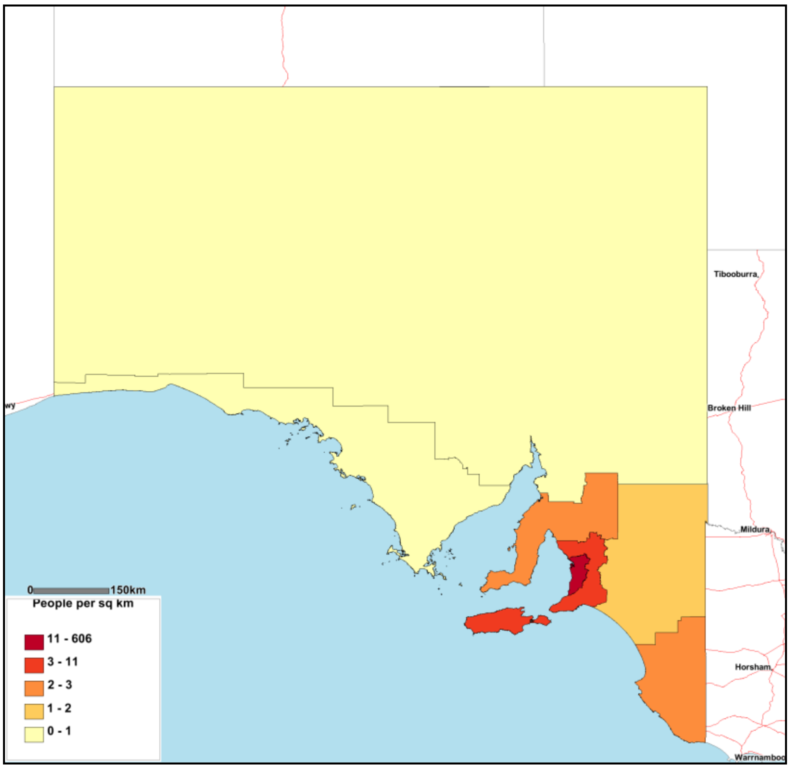


Figure 3-7: South Australia population density

Research method for the single case study

The single case study is aimed at understanding the actual house building process and investigation of the effect of construction commencement intervals and house design options on the completion time. To do so, an actual house building process is modelled and different scenarios of construction commencement intervals and house design options are simulated.

Case study selection: The case study used is a transportable house production located in Adelaide, South Australia. This process aims at production of the houses on the company's site and transporting them to the final location. Although the construction process is undertaken offsite, it follows the same methods as on-site construction and, therefore, it is an appropriate case for the study and enables the research to generalize the results for on-site house building operations. Further, because houses in production process were in different stages of construction, it was an advantage for the researcher to see the whole process of house building in one place and in a short period of time.

Data collection: The data related to this process are collected through site observations, interview with sub-contractors and crews, interview with site manager and document analysis. The documents include the sub-contractors invoices and material orders. The data used for the modelling consist of most often time needed for activity completions, the logic and relationship between activities, list of sub-contractors and crews, general schedule of single house construction, material needed for activities and their related costs, and idle time in the process.

Analysis: Using the data mentioned above, the house building process is mapped and modelled. A general purpose simulation software called Simul8 is used as a platform for modelling of the process. This platform possesses some default components such as work entry, work station, inventory and resources. It allows modelling of a specific situation through programming. This ability is used for controlling the workflow and variability, and for reporting house completion time, idle time and resource utilization.

Following the modelling, different scenarios are simulated and their effects on house completion time are reported. Chapter seven further discusses this model, its components and abilities.

3.4 Research design and thesis structure map

Following figure demonstrates the research methods for each objective and the related chapter in the thesis. Further, two levels of the research namely industry and company are shown in this figure.

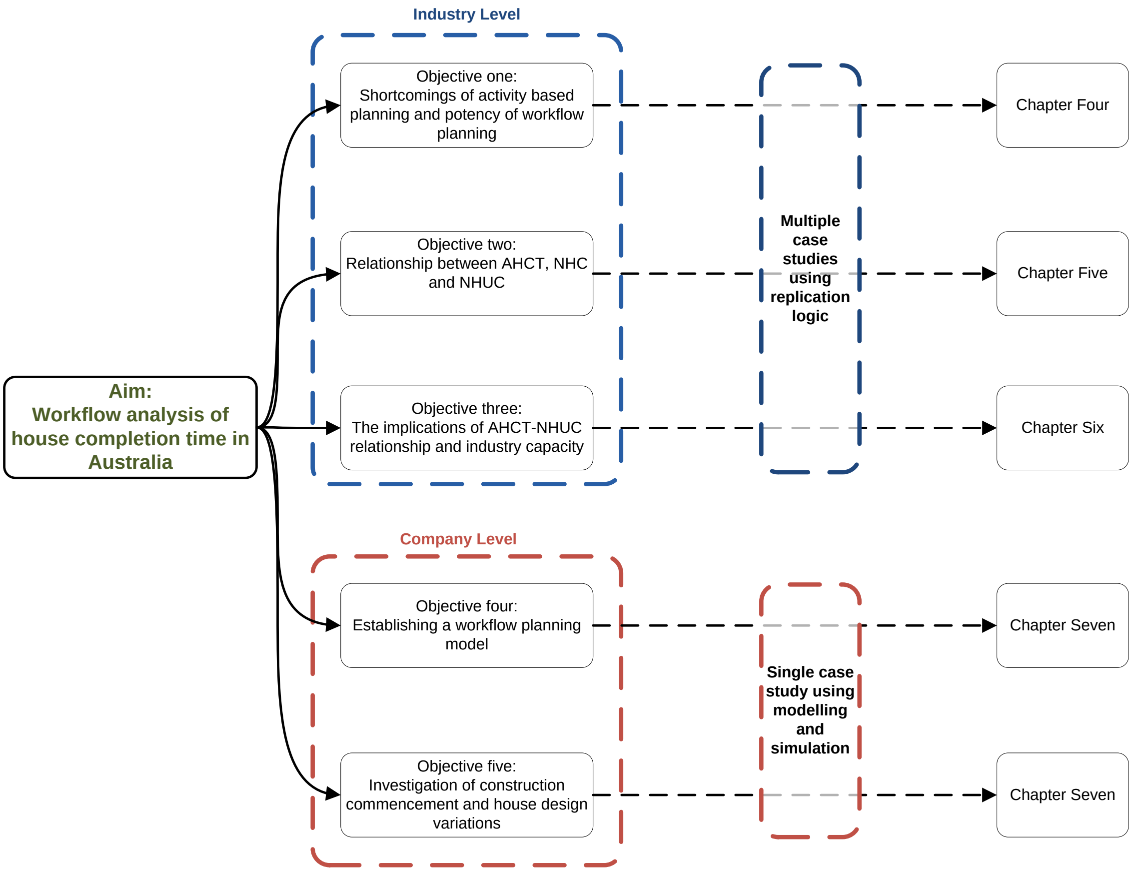


Figure 3-8: Map of research objectives, methods and their related chapters

3.5 Chapter summary

The research aim and objectives were clarified in this chapter. It was explained that the aim of the research is the investigation of house completion time using the workflow-based planning approach. The objectives were defined in order to address this aim. These objectives focused on investigation of house completion time at industry and company level.

The industry level objectives of research include the confirmation of shortcomings of the activity-based planning approach in explanation of changes in completion time in Australia. The investigation of relationships between average house completion time, number of house completions and number of houses under construction was another objective. Further, the implications of this relationship were added to the objectives to seek the benefits of the workflow-based planning approach for industry analysts.

Two more objectives were added to the research objectives that address the issues around house completion time at company level. These objectives include the workflow modelling of an actual house building process, and exploration of the effect of construction commencement intervals and house design options on completion time.

The research was designed according to a framework suggested by Creswell (2009). This framework consists of philosophical worldview, strategy of inquiry and research method. It was shown that this research has a postpositivist philosophical worldview, its epistemological stance is objectivist, and its ontology is realism.

Quantitative case study was determined as the appropriate strategy of inquiry. However, this design was divided into two different approaches for research at industry level and company level.

A multiple-case study approach was selected for the investigation of completion time at industry level. The research method for this part of design includes definitions and data collection, research logic and selection of case studies. It was explained that five state case studies and one national case study are appropriate cases for this research. New South Wales, Victoria, Queensland, Western Australia, South Australia, and the whole country as a meta-case, are the case studies.

The research for the analysis at company level was designed as single-case study. The data needed for this case were determined and the method and tool for the modelling and simulation were selected. A house building process was chosen for the case study.

The next chapter starts the analysis of the house building industry and targets the first objective of the research.

4 CHAPTER FOUR - AUSTRALIAN AVERAGE HOUSE COMPLETION TIME

4.1 Introduction

Completion time of a construction project is always a major concern for all stakeholders. For the Australian house building industry, completion time has serious investment implications. Simultaneously, housing customers remain financially and emotionally engaged in the process while waiting for their home to be delivered. In this situation, any increase in completion time results in further capital investment, more management effort, and reduced customer satisfaction.

According to the Australian Bureau of Statistics (ABS) (2008), the house building industry in Australia has experienced an increase in the average completion time of houses since 2000. The average completion time for new houses at the beginning of 2000 was 1.8 quarters, reaching 2.4 quarters by the end of 2008. These figures show that house buyers had to wait 35 percent longer in 2008 than in 2000. The increase in some states is more dramatic. For instance, Western Australia has faced a 70 percent increase during the same period.

Considering that houses are the dominant type of dwelling in Australia, these figures show the importance of research on house completion time. However, finding solutions for the increase in completion time requires a proper understanding of the house building industry and the major factors affecting house completion time. This chapter investigates these factors using different approaches in construction project planning.

Two main planning approaches are considered; namely, activity-based planning and work-flow-based planning. The former is the basis for most of the conventional planning methods used in construction, and the latter forms the foundation for production planning methods common in manufacturing. This research uses both of these approaches to explain the reasons for the increase in the average house completion time.

The case studies in this research comprise five cases at the state level, and a meta case at the national level. The state cases are Australia's largest states, namely, Victoria (Vic), New South Wales (NSW), Queensland (Qld), Western Australia (WA) and South Australia (SA).

Note that "average house completion time" is called in some places in this chapter "completion time" for brevity. Therefore, whenever the term "completion time" appears in the text, it directly refers to "average house completion time" in the house building industry.

4.2 Activity-based planning approach

The main focus of most of conventional construction planning methods is on the activities. Network planning (CPM, PERT) and line of balance are two examples of such planning techniques, which are based on activities. With this focus, project planning leads to activity planning and the duration of the project relies directly on the duration of activities. Consequently, any change in activity durations would result in a change to project duration.

In the activity-based planning approach, the duration of the activities can be indicated by two parameters, namely, the activity's scope of work, and the production rate of resources. Using this approach, any loss of production rate or extension of the scope can result in an extension in the activity duration, and therefore, project duration. Therefore, according to the activity-based planning approach, the reason for the increase in project duration is either the loss of production rate or the extension of the scope of work.

In the case of the house building industry, these two parameters can be traced by the quarterly number of house completions as a proxy of the industry's production rate, and the average house floor area as a proxy of the scope of work.

The next two sections investigate the association between these two parameters and average house completion time in the Australian house building industry.

4.2.1 Quarterly number of house completions

As mentioned above, the activity-based planning approach suggests that the increase of completion time might be because of loss of production rate. The trend of production rate can be found by the quarterly number of house completions. Therefore, the increase of average house completion time is expected to be concurrent with decrease in the number of completions. The trend of average house completion time and quarterly number of house completions can be derived from the actual data reported by the ABS (2009). Drawing of these trends on a common graph shows the existence of any correlation.

This research has been undertaken on six cases. Five of these cases are Australia's larger states. The final case is at the national level and covers the whole Australian house building industry

Victoria

Since the research is undertaken at RMIT University in Victoria, the analysis started with this case and then extended to other states and the whole country. The comparison between the production rate trend and the average house completion time trend is best illustrated in Figure 4-1. The graph shows that the minimum average house completion time in this state was in 2002 when it reached 1.9 quarters. After 2002, the completion time increased to around 2.5 quarters in 2008. However, the production rate of the industry remains constant during this period. The average production rate (illustrated in Figure 4-1) is around 8,000 houses per quarter.

Figure 4-1 also illustrates that the trend of production rate does not match the trend of completion time. In other words, the construction industry has maintained a more-or-less constant production rate while the completion time has been increasing dramatically. This refutes the proposition suggested by activity-based planning approach, which suggests that the increase of the average house completion time may be the result of a decrease in the industry's production rate.

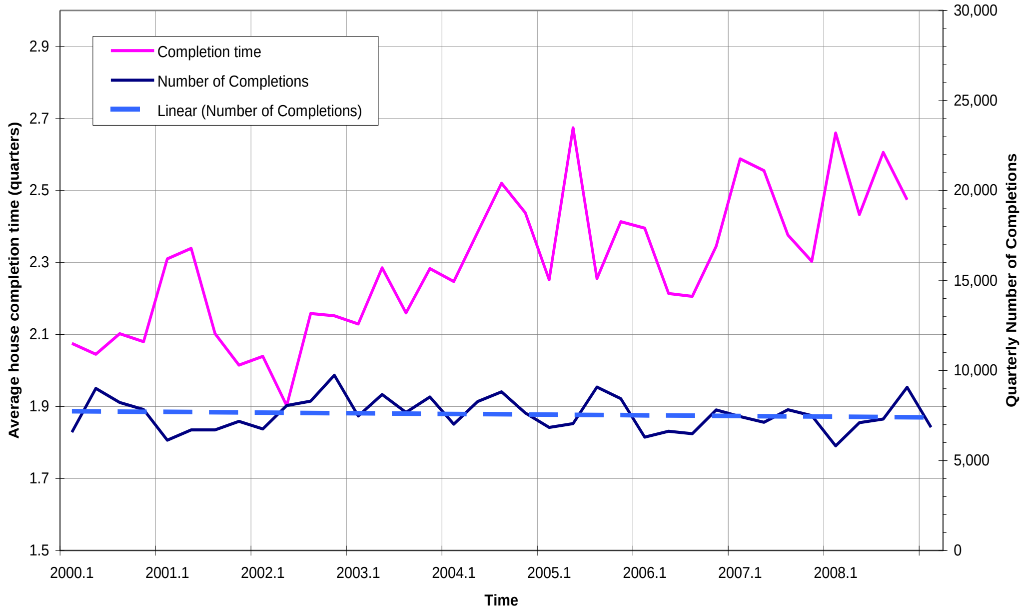


Figure 4-1: Average house completion time and quarterly number of completions in Victoria

Western Australia

Western Australia has seen an increase in average house completion time of around 70 percent between 2000 and 2008. However, the main growth in this state did not start until the end of 2001. The average house completion time in the fourth quarter of 2001 was 1.6 quarters. This duration reached 3.2 quarters at the end of 2008, showing an almost 100 percent increase in 7 years. Figure 4-2 clearly shows this dramatic increase.

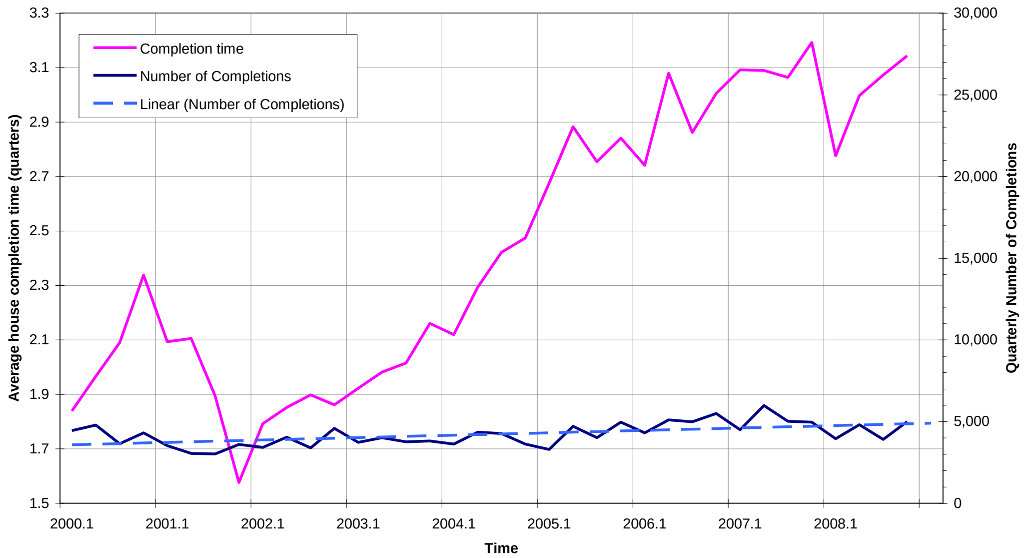


Figure 4-2: Average house completion time and quarterly number of completions in Western Australia

In the same period, the production rate of the industry was around 4,000 houses per quarter. The industry even had a slight growth in production rate in 2006 and 2007. Nevertheless, this increase could not help the industry finish houses in a shorter time. Therefore, the growth of the average house completion time cannot be the result of production rate loss. Western Australia is the second case whose behaviour cannot be adequately explained by the activity-based planning approach.

Queensland

The average house completion time in Queensland has a similar trend to the first two cases. This state has been facing an increase in completion time since the end of 2001 and reached 2 quarters at the end of 2008. This increase has taken place whilst the production rate has remained constant. Figure 4-3 shows that the number of completions in Queensland has remained around 7,000 houses per quarter.

Beside the existence of different trends for completion time and production rate in this state, it can be seen in Figure 4-3 that there were peaks and troughs in the completion time in this period, but these changes cannot be seen in the production rate. Therefore, it can be concluded that the completion time in Queensland is not associated with production rate. Hence, Queensland will be the third case in which the activity-based planning method could not explain the increase in the completion time.

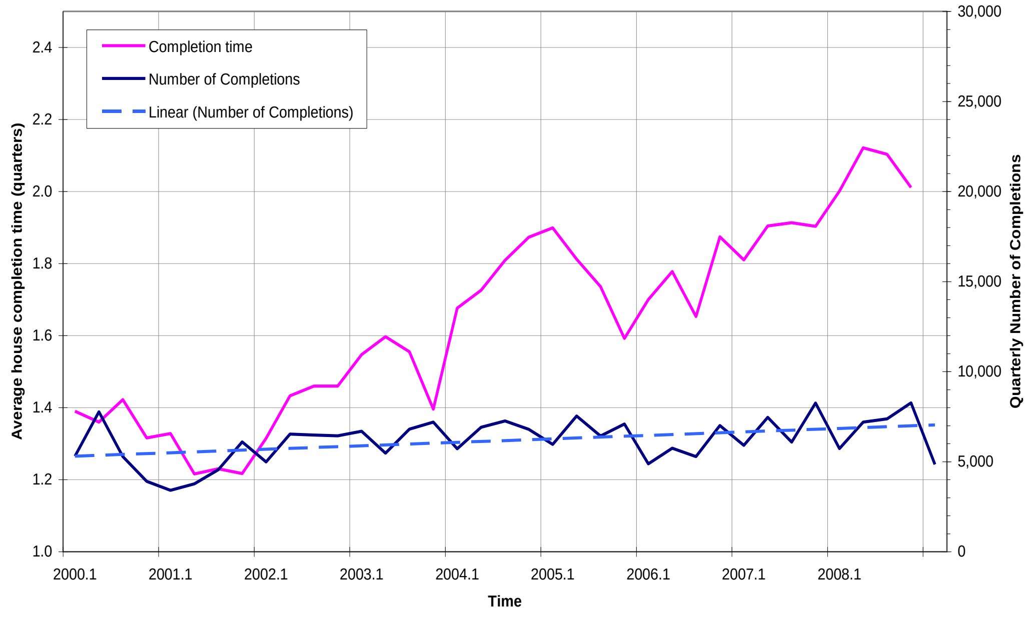


Figure 4-3: Average house completion time and quarterly number of completions in Queensland

New South Wales

The average house completion time in New South Wales (NSW) follows the same trend as the previous cases. However, this state has a different production rate trend compared to other states. In this state, the production rate has been declining since 2000. The production rate has almost halved during this period and the completion time has been affected by this reduction. The trends in NSW can be explained by the activity-based planning approach, the decline being the reason for the increase in completion time.

New South Wales is the only case that supports this proposition, and provides a valuable comparative case (Yin, 1994). Section 4.3.1 explains the phenomenon discovered in NSW.

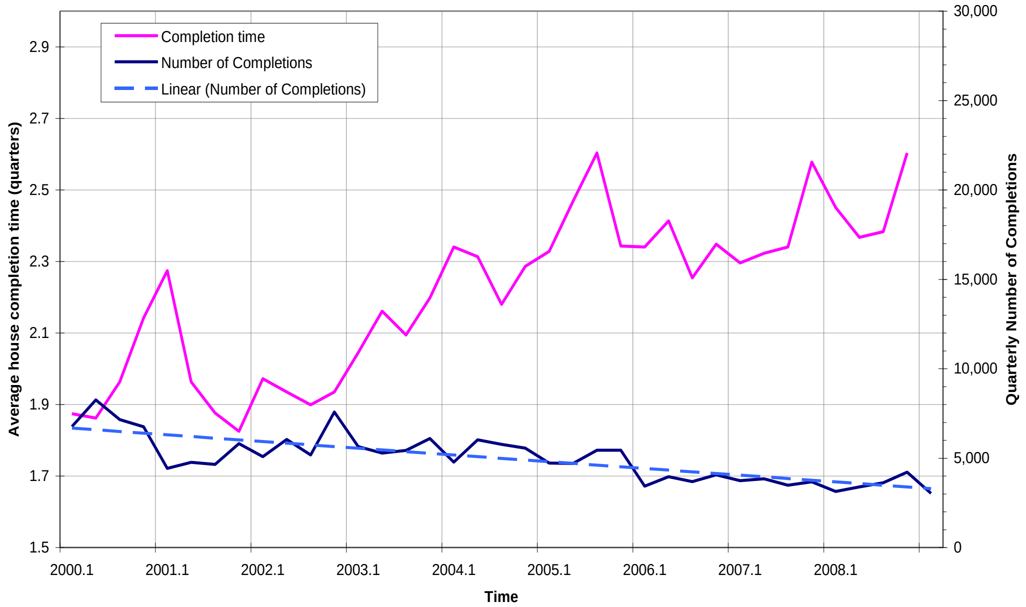


Figure 4-4: Average house completion time and quarterly number of completions in New South Wales

South Australia

South Australia is the final case at the state level. This state has also seen an increasing average house completion time since 2000. The production rate in South Australia has, however, remained almost constant. There is no loss in the production rate that can be considered as a reason for the increase in the completion time. Further, there are variations in the completion time that cannot be seen in the production rate.

So far in four of five cases at the state level, the increase in average house completion time has not been adequately explained by the proposition suggested by the activity-based planning approach.

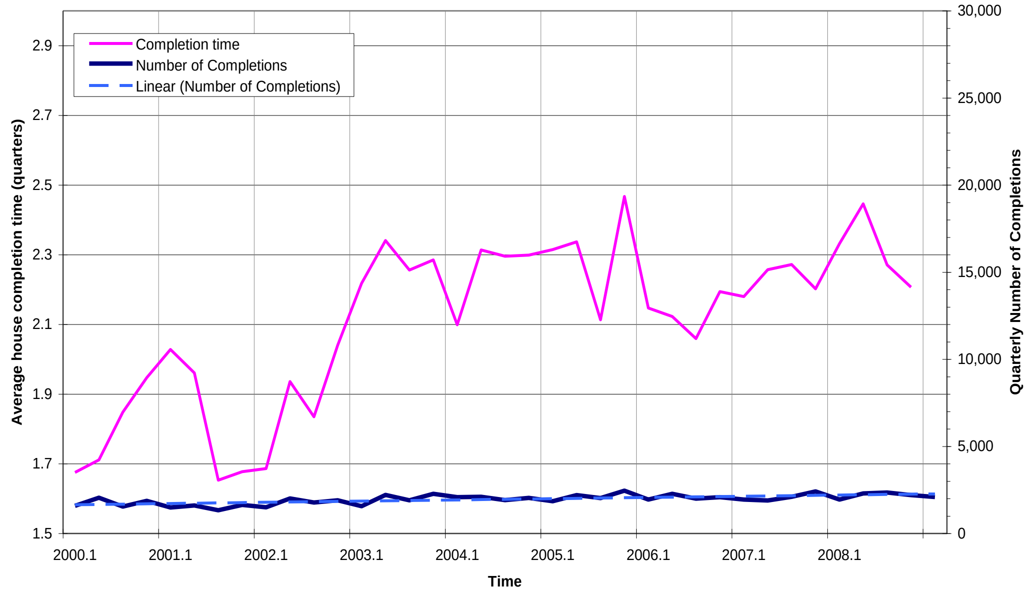


Figure 4-5: Average house completion time and quarterly number of completions in South Australia

Australia

The final case is the whole Australian house building industry. The Australian average house completion time has gone up from 1.8 quarters at the beginning of 2000 to 2.44 quarters at the end of 2008 (Figure 4-6).

The linear regression on the quarterly number of completions shows that the production rate in the Australian house building industry has been swinging around 27,000 houses. This regression is almost horizontal in this period, which shows the consistency in the production rate between 2000 and 2008.

It means that while the industry has maintained its productivity, average house completion time has grown. Once more, the production rate trend does not match the completion time trend. The activity-based planning approach does not adequately explain the increase in completion time.

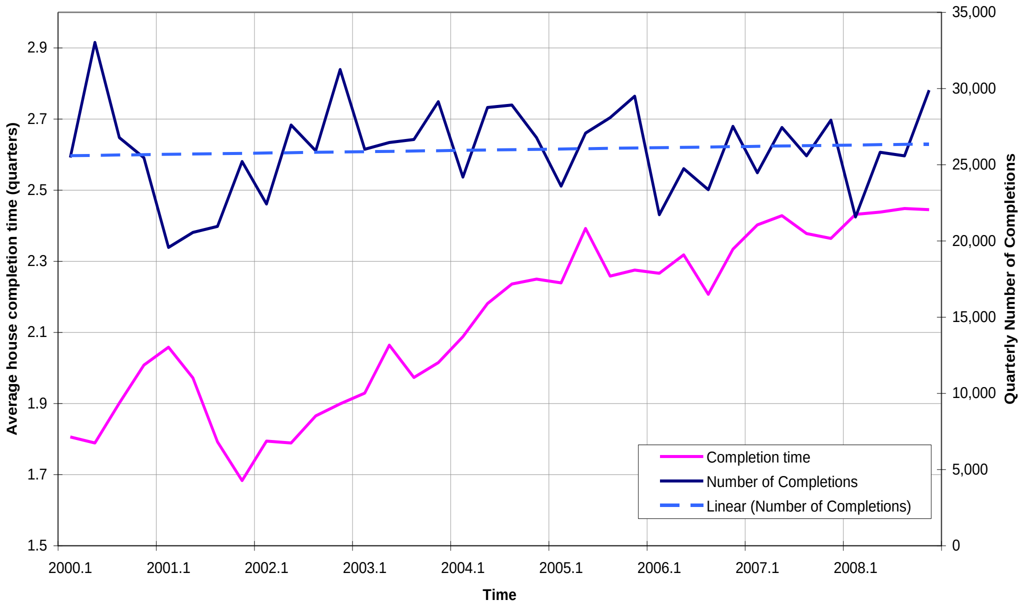


Figure 4-6: Average house completion time and quarterly number of completions in Australia

Section summary

This part of the research investigated the reason for the increase in the Australian average house completion time utilizing the activity-based planning approach. According to this planning approach, the loss of production rate lengthens the activities and consequently the project's duration. Therefore, the increase in average house completion time might be because of a loss in production rate.

This proposition has been investigated using six case studies. In five of the cases, no production loss was observed in the past decade. It is argued that according to the trend of number of house completions and average house completion time, the increase in the completion time of the houses cannot be the result of production loss and therefore, the activity-based planning approach fails to explain this observation.

Figure 4-7 shows that the increase in the completion time is a general trend in all states, with Western Australia showing an extreme increase in completion time. These graphs also share a similar trend for production rates, except in New South Wales. In all states apart from New South Wales, the production rate has been constant and no loss of production rate has been observed during this period.

In the next section another proposition proposed by the activity-based planning approach is examined, namely the effect of scope of work on the completion time.

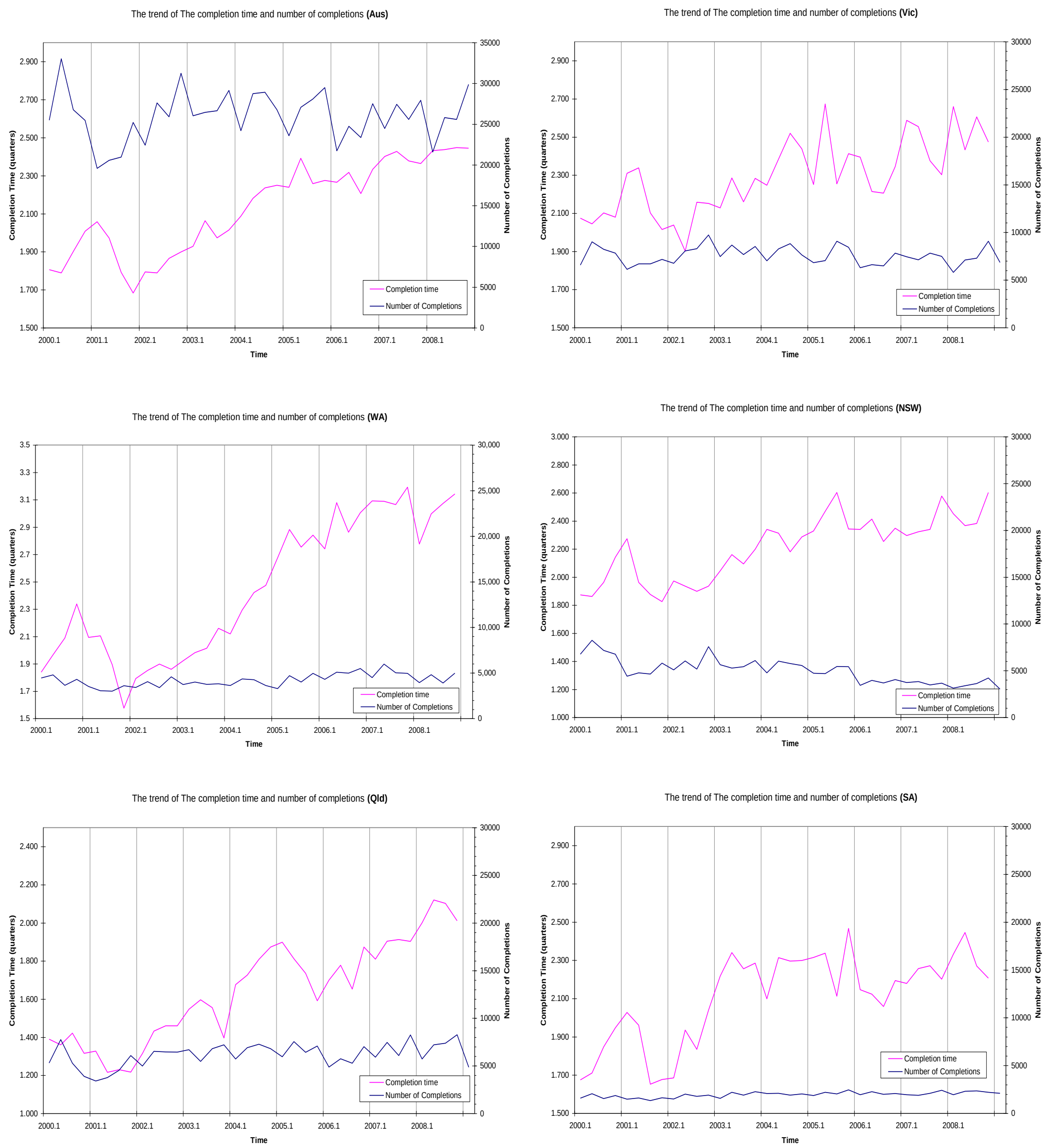


Figure 4-7: Average house completion time and the quarterly number of completions in Australia and different states

4.2.2 Average house floor area

Activity-based planning approach suggests that another reason for the extension in the completion time is a change in project scope. To investigate this hypothesis, the average house floor area was used as a proxy for project scope and was analysed with the trend of average house completion time. Average house floor area was derived from ABS (2010) data and is reported in appendix A.

Since the focus is on the Australian house building industry, the same six cases were utilized; one case at the national level and five at the state level. The following sections show the effect of average house floor area on the average house completion time.

Victoria

Victoria shows inconsistency between the trend of the average house floor area and average house completion time (Figure 4-8). The completion time in this state experienced a 35 percent increase between 2002 and 2007, yet the average house floor area grew by only 10 percent.

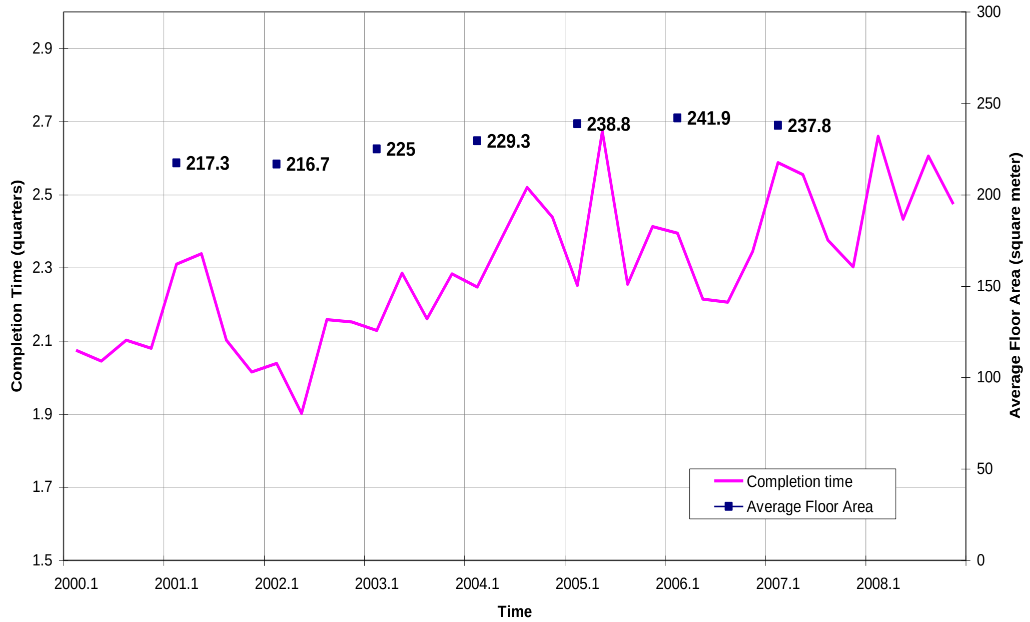


Figure 4-8: Average house floor area and average house completion time in Victoria

The trend of both parameters in this state is increasing but these increases do not match each other. For example, the completion time in Victoria fluctuates even though the average floor size does not show any fluctuation. Based on the activity-based planning suggestion of the association between completion time and the scope of work, an increase in the scope should cause the completion time to increase; while a decrease should have the reverse effect. In the case of Victoria, however, the completion time both increases and decreases without apparent correlation to the increasing average floor area. Subsequent cases for the other states further emphasises this.

Western Australia

The same phenomenon can be seen in Western Australia (Figure 4-9). In this state, the average house completion time also increased dramatically without any dramatic increase in the average house floor area. In fact, the completion time doubled between 2002 and 2007 with average floor area having only grown by 5 percent. This is the second case that demonstrates that activity-based planning is inadequate for explaining the increase in house completion time.

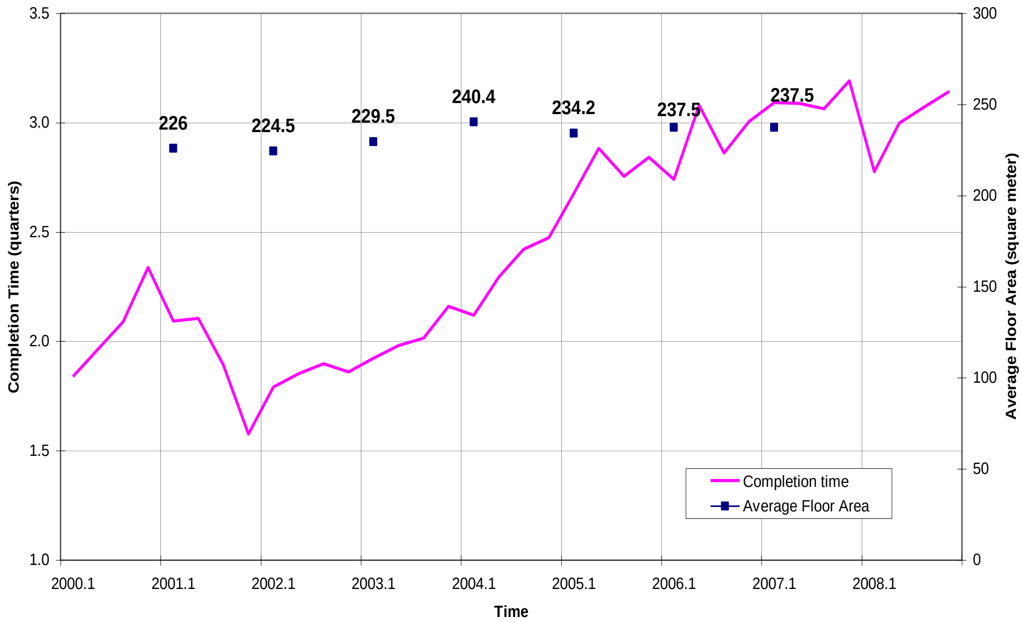


Figure 4-9: Average house floor area and average house completion time in Western Australia

New South Wales and Queensland

To avoid repetition, these two cases are explained together in this section. In the previous two states, the completion time grew dramatically, with only modest average house floor area growth. According to the ABS, the average floor area in New South Wales increased by 10 percent while the completion time increased by 35 percent (Figure 4-10). Queensland also followed the same trend where the increasing trend of completion time did not match the trend of the average floor area (Figure 4-11).

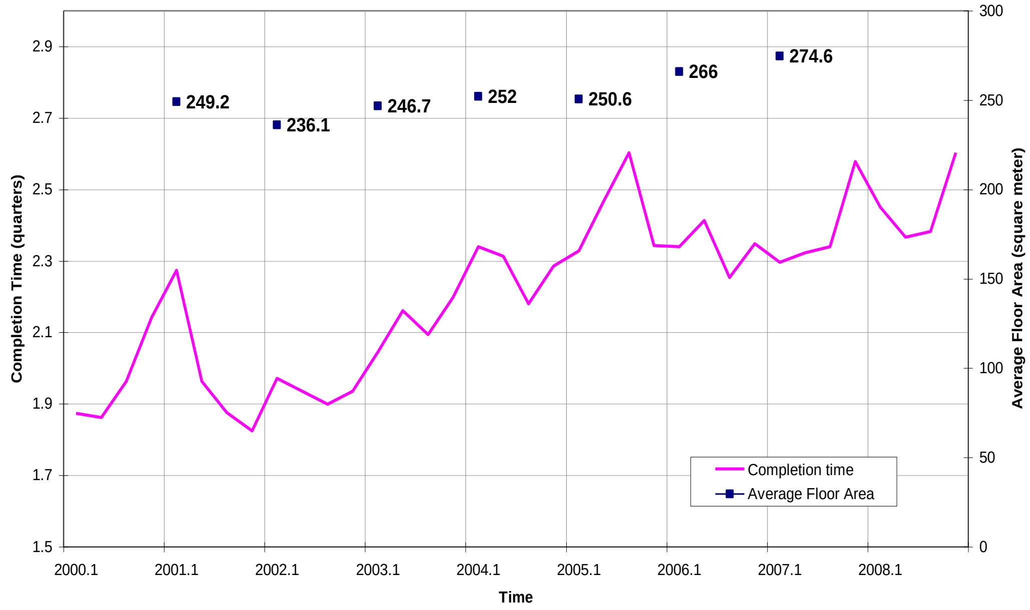


Figure 4-10: Average house floor area and average house completion time in New South Wales

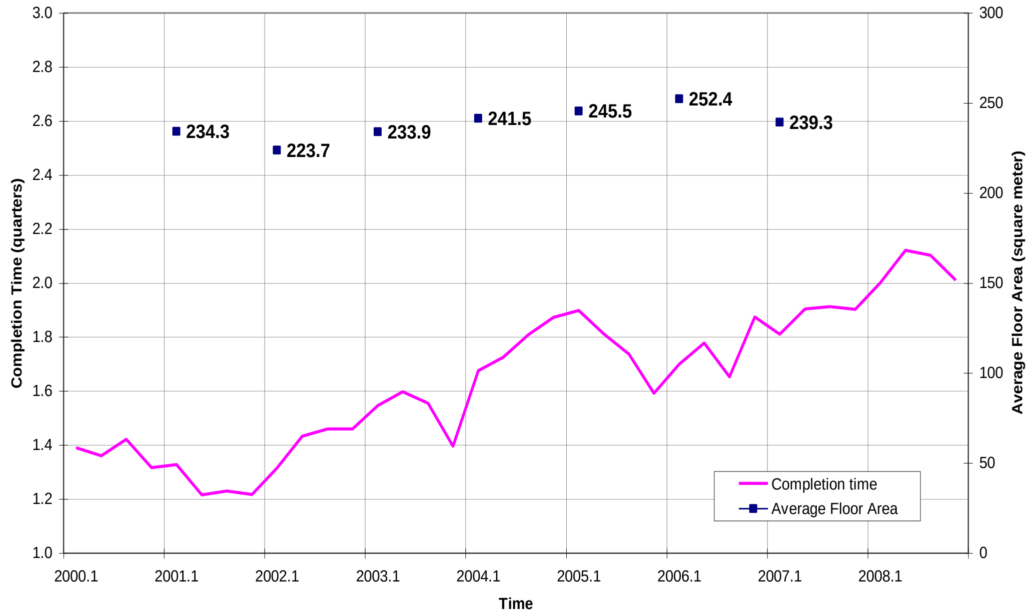


Figure 4-11: Average house floor area and average house completion time in Queensland

South Australia

South Australia is the state that strongly refutes the suggestion of the impact of the average house floor area on average house completion time. The average floor area in this state dropped from 206m^2 to 191.5m^2 (Figure 4-12), while at the same time the completion time climbed from 1.7 to 2.4 quarters. This 40 percent increase in completion time, when the average size of houses reduced, strongly contradicts the activity-based planning approach for explaining the increase in the average house completion time.

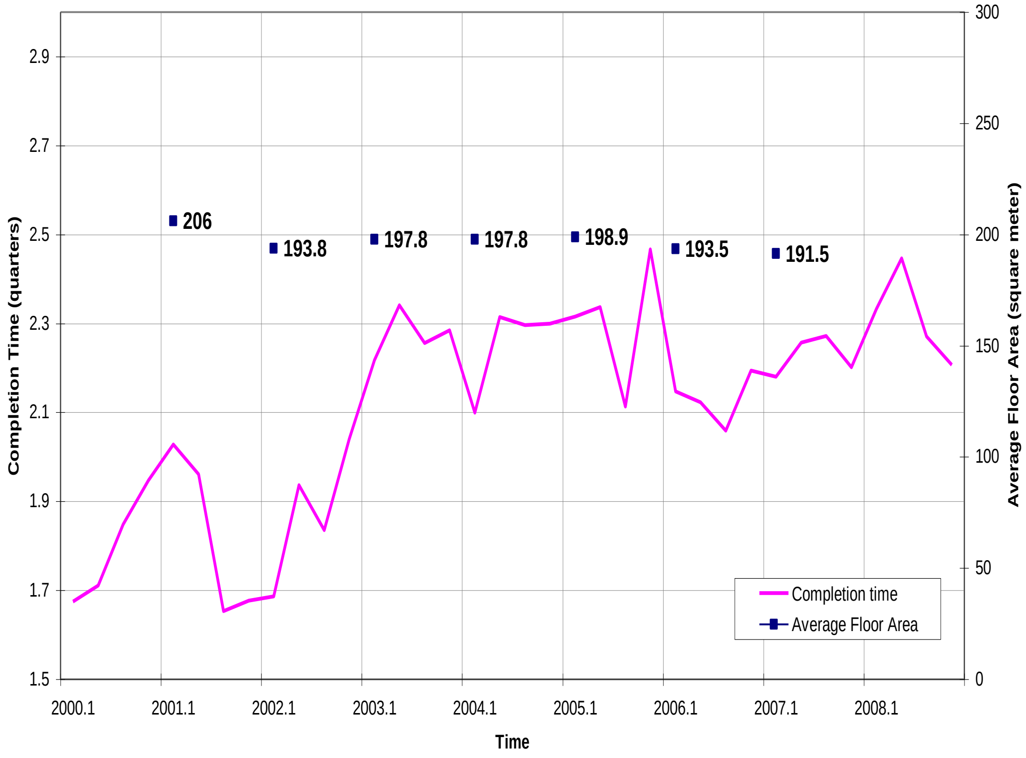


Figure 4-12: Average house floor area and average house completion time in South Australia

Australia

The trend of average house completion time in Australia was explained in section 4.2.1, which demonstrated that it had increased by 35 percent since 2000. In the same period, the average floor area for houses had gone up by 5 percent. Similar to previous cases, this percentage does not match the increase in the completion time. Figure 4-13 shows this inconsistency.

While the completion time grew, the average floor area remained around 235m^2. There was not any dramatic change in the average floor area over this period that might explain the increased completion time. Therefore, the reason for the dramatic increase in the average house completion time cannot be attributed to an increase in scope and, therefore, length of activities. This further demonstrates the inability of the activity-based planning approach at explaining the housing industry's behaviour.

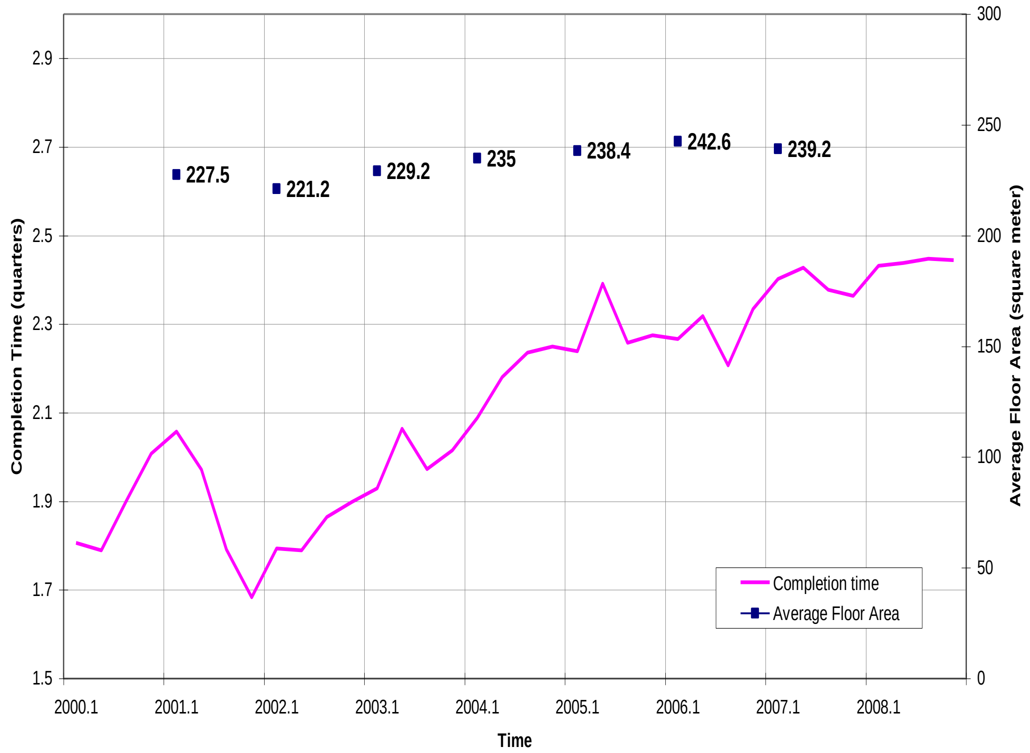


Figure 4-13: Average house floor area and average house completion time in Australia

Section summary

In all states, house size has had limited impact on completion time. The size of houses has grown during the years 2000-2008, but without any association to the increase in the average house completion time. In fact, South Australia has shown a contradictory trend where the average house floor area decreased as the completion time rose dramatically.

Figure 4-14 summarizes Figures 4-8 to 4-13. In this figure, the overall trend in Australia and its different states can be seen. Considering the completion time trend in all states and the country, it can be concluded that house size does not affect completion time, when viewed from an activity-based planning perspective.

However, the growth of completion time is an undeniable fact in the Australian house building industry. It has been shown that this increase cannot be explained by the activity-based planning approach where the main focus is on the scope of work and production rate of resources. Therefore, another factor affecting the average house completion time needed to be found. The following section tests an alternate approach to find this factor and explain the reason behind this increase.

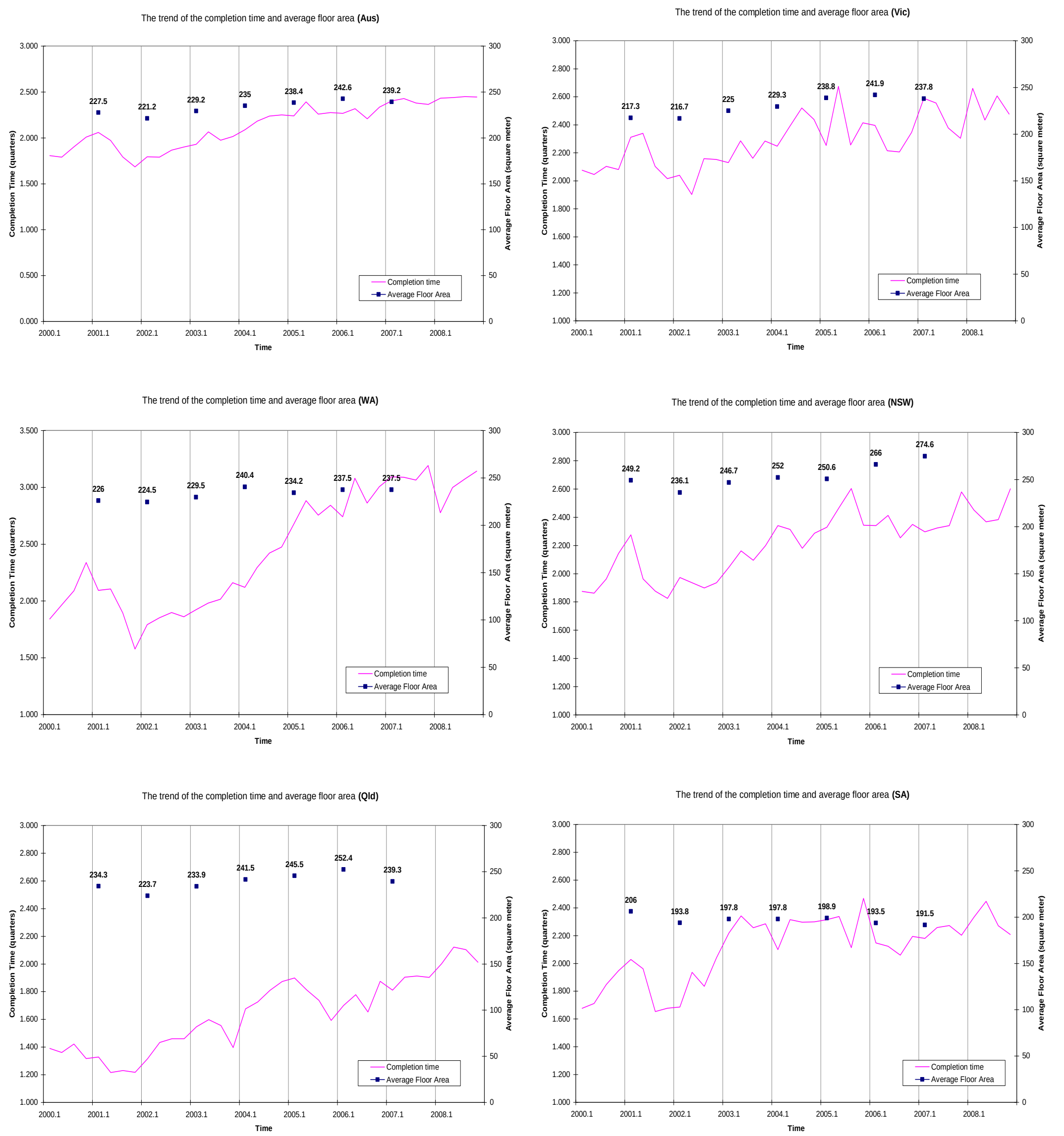


Figure 4-14: Average house floor area and average house completion time in Australia and different states

4.3 Workflow-based planning approach

The first objective of the research was to show the shortcomings of the activity-based planning approach and the potency of workflow-based planning approach in explanation of changes in house completion time. The first part of this objective was achieved in the previous section. This section focuses on the workflow-based planning approach and its potentials, particularly in explanation of changes in completion time.

It has been explained in Chapter two that in a production system, cycle time is influenced by work in process. In the house building industry, houses are the products. The cycle time of these products represents house completion time and the work in process is in fact houses under construction. With these definitions, it can be suggested that according to the workflow-based planning approach house completion time is influenced by the number of houses under construction. This idea was demonstrated in Chandler, Arizona, by Bashford (2005) and this research attempts to study its validity in the Australian house building industry.

This section is the starting point for investigation of house completion time using the workflow-based planning approach. This is the main aim of the study and, therefore, the time span of the research is extended from past decade to the period that the data is available. The house completion time data are available for the period of 1987 to 2008 and the data for number of houses under construction are also available for this period. Thus the period of study in this section and following chapters is 1987 to 2008. Since this time span covers the past decade, the result of this section is comparable with the result of previous section.

4.3.1 Number of houses under construction (NHUC)

Previous sections were dedicated to the investigation of the possible effects of the production rate and average house floor area on average house completion time in Australia. This section investigates the correlation between average house completion time and the number of houses under construction. The actual data for these variables was collected quarterly by the ABS (2009) and are reported in appendix A.

In this section, the same method of monitoring and comparison of the two parameter trends is used and the same six cases as in the previous sections are studied.

Victoria

The Victorian house building industry shows a visual correlation between the number of houses under construction and the average house completion time (Figure 4-15). The first peak point for NHUC happens in the middle of 1989. This peak point is followed by a peak point in average house completion time almost one year later. The number of houses under construction then declines for 7.5 years until 1997 and there is a slight rise in mid 1994. In consistency with NHUC, the completion time declines from mid-1990 until 1998 for 7.5 years. This trend also shows a rise in mid-1995.

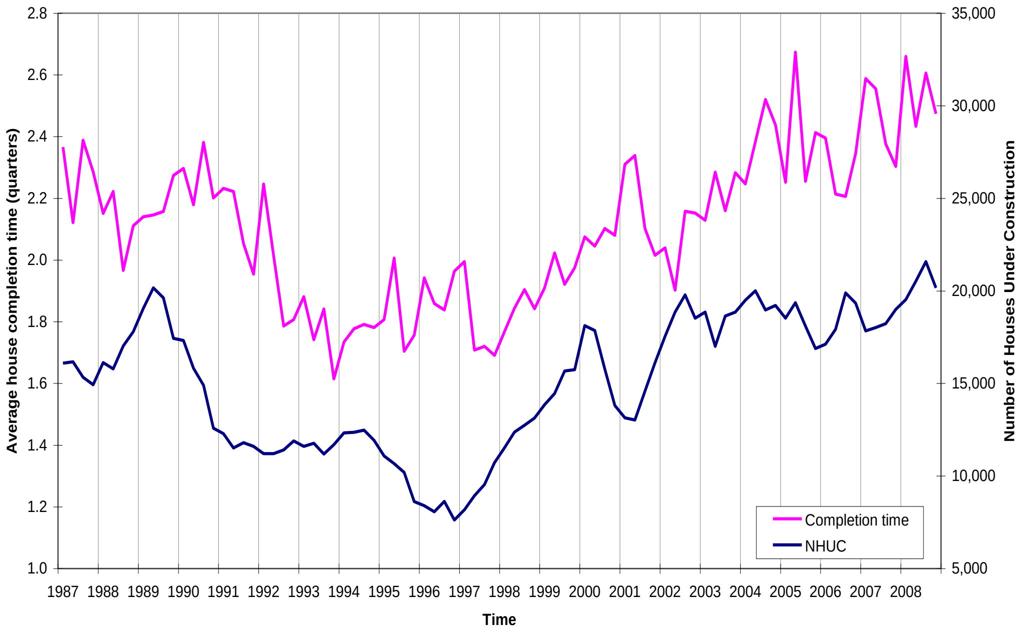


Figure 4-15: Number of houses under construction and average house completion time in Victoria

Comparison between these two trends in the past decade shows that the increase of house completion time is correlated with the increase in number of houses under construction. The number of houses under construction peaks in 2000 and the completion time peaks after a year. The growth of house completion time in the past decade starts from mid-2002. This growth is the result of the increase in the number of houses under construction in mid-2001.

The overall trend of these two parameters is similar and the correlation between them is visually realized. However, to complete this comparison and prove the correlation, the correlation coefficient between them is calculated. This coefficient for Victoria is 0.84, which is a positive correlation.

Note that this correlation happens with a lag. This lag can be seen in Figure 4-15. For example, the increasing trend of number of houses under construction after 1997 is lagged in average house completion time by almost a year, and peak points of number of houses under construction in 1989, 1994 and 2000 are followed by peak points in completion time in 1990, 1995 and 2001. Since this chapter is concerned about the existence of the correlation and not the details of the correlation, the explanation of this lag is postponed to Chapter five.

Western Australia

As shown earlier, the increasing trend of completion time in Western Australia since 2000 is not the result of the loss in the production rate or the increase of average house floor area. With number of houses under construction showing a strong correlation with completion time in Victoria; Western Australia acts as a refuting or confirming case for this correlation.

Figure 4-16 demonstrates that Western Australia shows the same behaviour as Victoria. This state has seen cycles of increase and decrease in the number of houses under construction; and each cycle is followed by a cycle in average house completion time. The NHUC in this state has had an increasing trend in the past decade. This increase started in mid-2001 with around 4,600 houses under construction, and it reached more than 16,500 houses by the end of 2006.

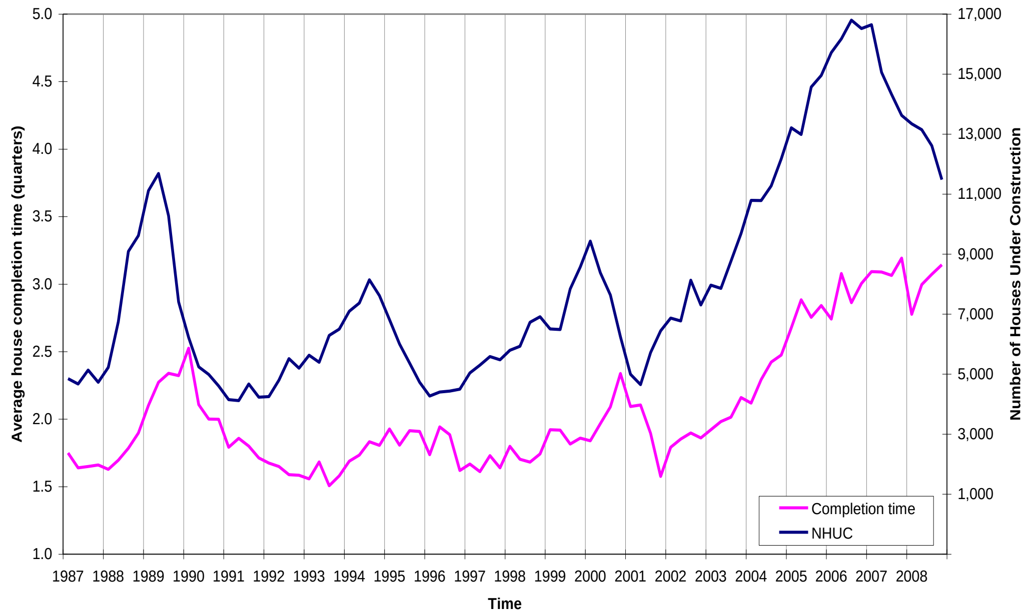


Figure 4-16: Number of houses under construction and average house completion time in Western Australia

The correlation coefficient measured for this state is 0.95, which suggests a high positive correlation. This state is the second case that shows the strength of workflow planning methods in the explanation of the house building industry's behaviour. In fact, in Western Australia, the NHUC and the average house completion time correlation is clearer than in the case of Victoria.

Note that Figure 4-16 also shows a lag between number of houses under construction and average house completion time trends. This is the same kind of lag observed in Victoria's case and is explained in Chapter five.

New South Wales

New South Wales was the only state in which the increase in average house completion time could possibly be explained by activity-based planning approach (Section 4.2.1). In this state, the loss of production rate was considered a reason for the increase in the completion time over the past decade. However, based on replication logic explained in chapter three, this case also needs to be investigated using the workflow-based planning approach (Figure 4-17).

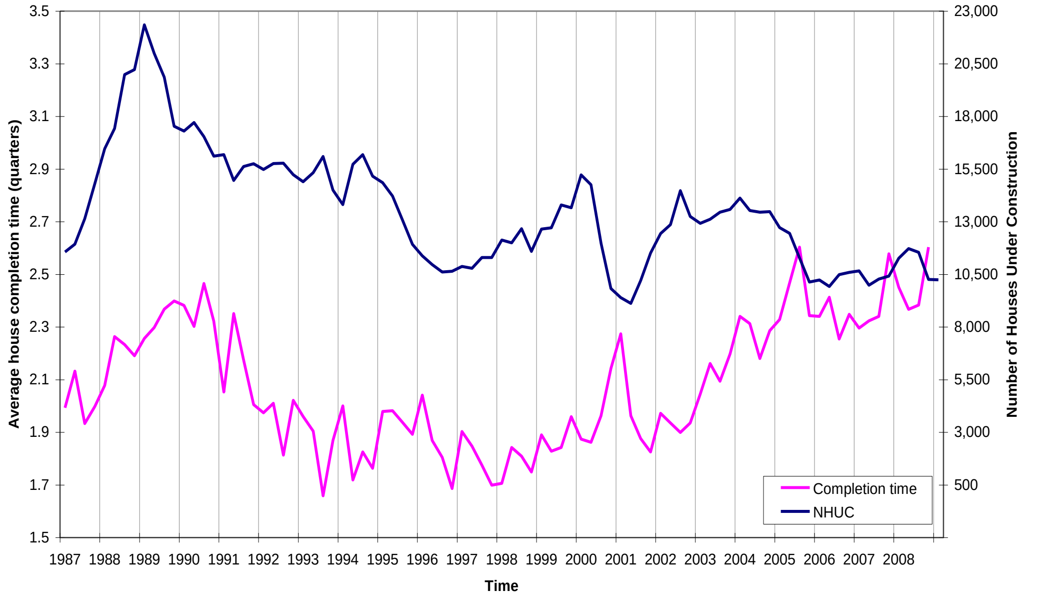


Figure 4-17: Number of houses under construction and average house completion time in New South Wales

According to Figure 4-17, the New South Wales house building industry shows two different reactions toward the change of NHUC. The first happens until 2002, in which the trend of completion time tracks the NHUC trend. The second is after 2002, when the trend of completion time does not follow that of NHUC. Although the NHUC decreases, the completion time continues to increase. For clarification of this argument the same graph as Figure 4-17 is drawn in Figure 4-18 covering the data between 1987 and 2002.

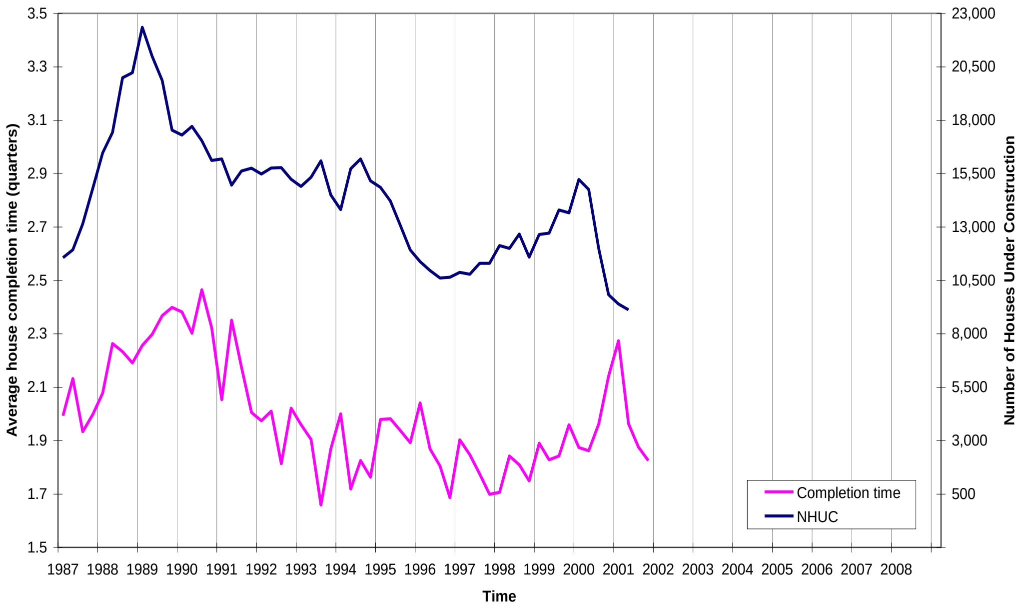


Figure 4-18: Number of houses under construction and average house completion time in New South Wales (1987-2002)

As can be seen in Figure 4-18, New South Wales shows the same correlation as other states between the average house completion time and NHUC up to 2002. The peaks in NHUC are followed by peaks in the completion time and the troughs are followed by troughs. The declining trend of NHUC between 1989 and 1997 results in a declining trend in completion time between 1990 and 1998. The correlation coefficient for this period is 0.71 and the lag between the two trends is also apparent. All these show a common behaviour with the previous cases and the applicability of the workflow-based planning approach for this period.

However, this correlation is not valid for the years after 2002. In these years, the NHUC declines (Figure 4-17), but instead of a decrease in completion time, the industry faces an increase. Therefore, there is an inconsistency with the previous cases. Yin (2009) suggests that when an inconsistency happens between case studies, the ability of the theory in explanation of the inconsistency shows the strength of the theory and its validity. Thus, the workflow-based planning approach, which is the subject of this study, was employed for investigation of this inconsistency.

Workflow-based planning approach argues that as long as the production rate is consistent, the completion time is affected by the number of houses under construction. However, when the industry faces a loss in the production rate, this parameter also exerts an influence and affects the completion time. To investigate this complementary explanation, the trend of the number of house completions as a proxy for production rate is drawn in the next figure.

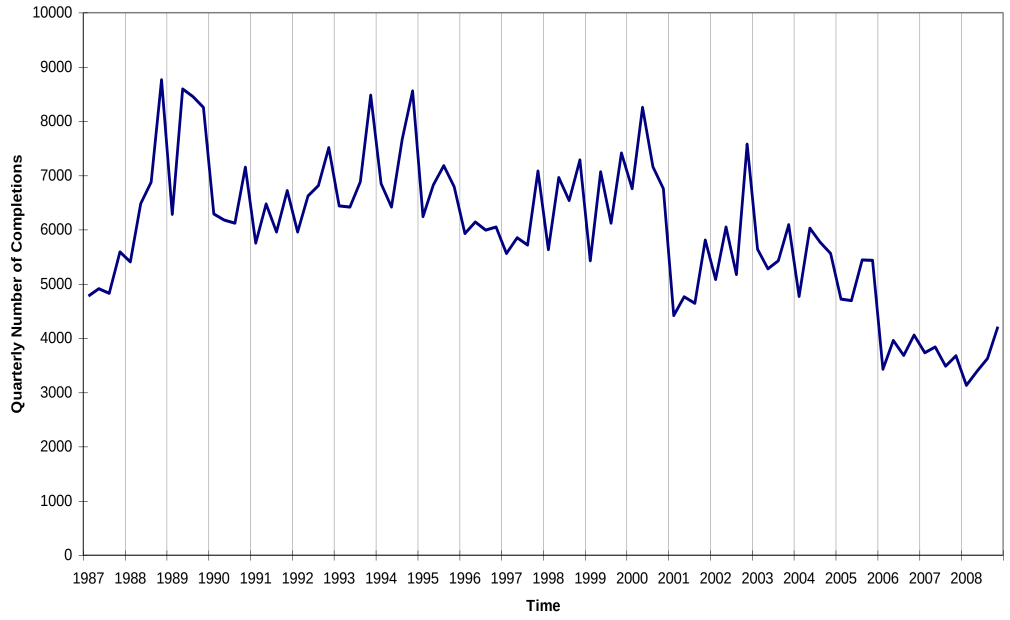


Figure 4-19: The quarterly number of house completions in New South Wales

Figure 4-19 shows that the production rate of the house building industry in NSW was around 7,000 houses per quarter until 2001. This production rate dramatically drops at the beginning of 2001 and recovers in the following two years, but from the end of 2002 the production rate continues to decline.

Considering Figure 4-19 and previous argument, the inconsistency of NSW with previous cases after 2002 can be explained. According to the workflow-based planning approach, the average house completion time in New South Wales is influenced by NHUC prior to 2002, because the industry had maintained its production rate. Further, since 2002, the industry has lost its production rate and this loss has affected the average house completion time, rather than declining NHUC.

In conclusion, as the workflow-based planning approach proposes, it has been shown that as long as the industry works with a consistent production rate, the changes in completion time can be explained by changes in number of houses under construction. However, with inconsistent production rate, the workflow-based planning approach suggests that this parameter should be also considered for analysing house completion time.

Queensland

Queensland is the next state to be investigated. In this state, the correlation coefficient between NHUC and house completion time for the whole period of study is 0.87. This correlation can be clearly seen after 1996 (Figure 4-20).

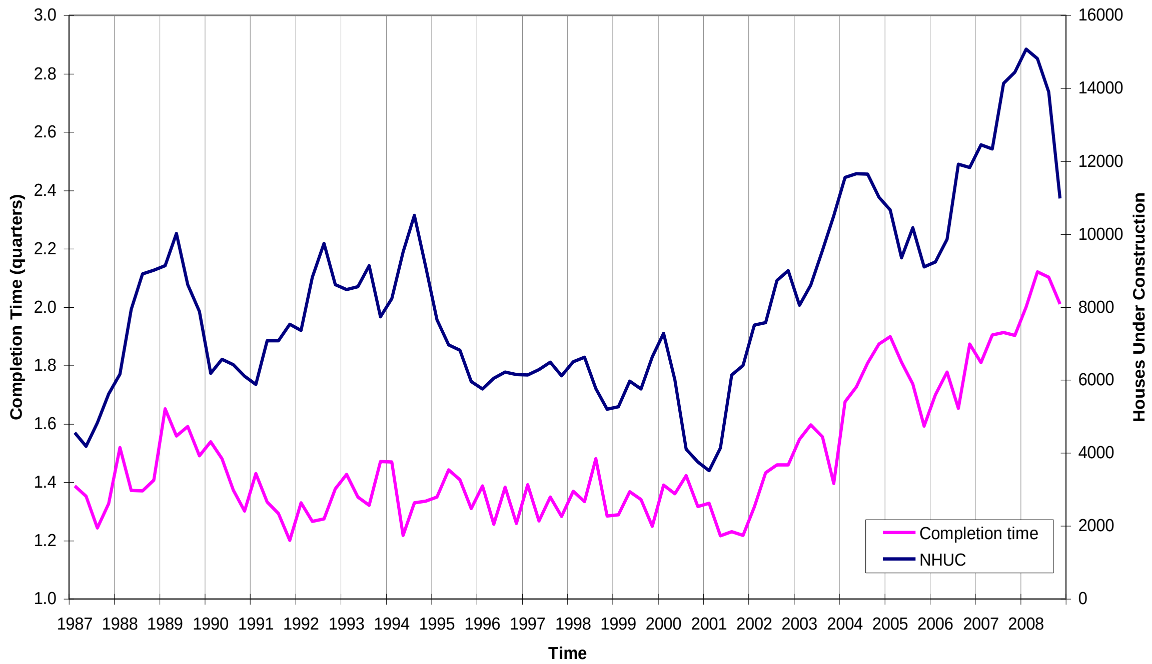


Figure 4-20: The trend of number of houses under construction and average house completion time in Queensland

Figure 4-20 shows that the NHUC peak points in mid-2004 and 2008 are followed by the completion time peak points. The overall increasing trend of NHUC can be seen in the average house completion time too. The same correlation happens between 1987 and 1991. Comparison of Figure 4-20 with Figures 4-3 and 4-11 shows the strength of the workflow-based planning approach against the activity-based planning approach in explanation of the reasons for the increase in average house completion time after 2000.

However, as Figure 4-20 illustrates, the years between 1991 and 1996 do not follow the same rule. NHUC is increasing in these years and has two clear peaks in 1992 and 1994. Consequently, the completion time is expected to be increasing and to have the same peaks. But as it can be seen in Figure 4-20, it does not show any dramatic change.

In the case of New South Wales, it has been shown that the inconsistency between the average house completion time and NHUC trends can be explained by the changes in the industry's production rate. To find the validity of this explanation in Queensland, the trend of the number of house completions as a proxy for production rate during these years is required. Figure 4-21 illustrates this trend.

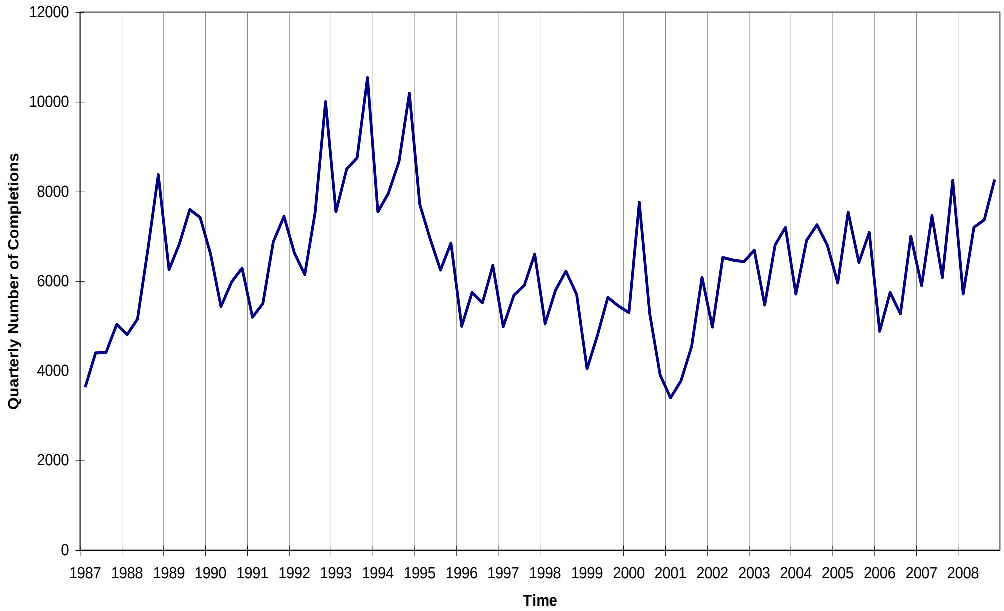


Figure 4-21: The quarterly number of house completions in Queensland

Figure 4-21 shows that number of house completions is around 6,000 houses per quarter after 1996. But the years between 1991 and 1996 face a dramatic increase. According to the workflow-based planning approach explained in New South Wales, this increase prevents completion time from following the increase in NHUC.

Figure 4-20 also demonstrates the existence of a lag between the trend of the number of houses under construction and average house completion time. The NHUC peak point at the beginning of 2000 is reflected after two quarters in completion time. The end of 2002 faced a peak in NHUC that was reflected in completion time in mid-2003. The NHUC troughs in 2001 and 2003, and parallel completion time troughs in these years, also point to the lag between these two parameters.

It should be noted that this part of the research is investigating the correlation between production rates, project scope, number of houses under construction, and the average house completion time. The explanation behind these correlations will be the subject of the next parts of the research (Section 5.2).

South Australia

Section 4.2.1 showed that the increase in average house completion time since 2000 was not the result of production rate loss. This increase was not the result of an increase in the scope of work either. In fact, the average house floor area decreased during this period, which should make the average house completion time shorter; however, the actual data showed a contrary trend.

Figure 4-22 is the output of a comparison between the number of houses under construction and the average house completion time in South Australia. It shows that NHUC has had an increasing trend since 2001 that matches the increasing trend of completion time. The steady trend of completion time between 1996 and 1999 is also consistent with the trend of number of houses under construction. This steady state leads to a peak point at the beginning of 2000 which is reflected in the average house completion time at the start of 2001.

The correlation coefficient between NHUC and house completion time is also calculated and its value is 0.82. This and the visual comparison suggest that the workflow-based planning approach, linking the completion time and number of houses under construction, adequately explains the trends in South Australia.

The only period that does not show the correlation between these two parameters is 1994-1996. In this period, the decrease in NHUC is not followed by a decrease in the average house completion time. Queensland and NSW have shown that whenever the correlation is not apparent, there is a change in the production rate. In the case of South Australia, the production rate in this period shows a dramatic drop from 2,700 to 1,000 houses per quarter. This confirms the prediction of the workflow-based planning approach.

Following previous cases, this case also shows a lag between the changes in number of houses under construction and the effect of these changes on average house completion time.

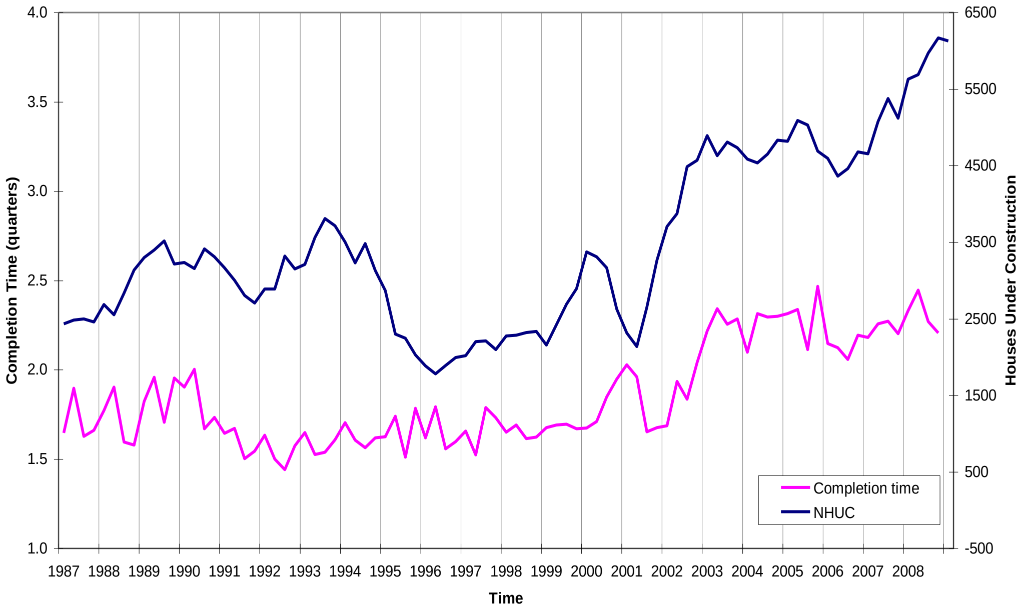


Figure 4-22: The trend of number of houses under construction and average house completion time in South Australia

Australia

The previous five cases were Australian states. These cases have shown that the workflow-based planning approach can explain the trend of average house completion time at state level. This section aims at the same kind of investigation at the national level. Figure 4-23 is the result of this investigation.

Contrary to the production rate and the average house floor area, the number of houses under construction shows a strong consistency with average house completion time. As can be clearly seen in Figure 4-23, the average house completion time and NHUC follow similar trend. The rise in NHUC is followed by a rise in completion time and a fall is followed by a fall. Therefore, as is suggested by the workflow-based planning approach, there is a strong correlation between these two parameters in the Australian house building industry. This correlation is also evidenced by the correlation coefficient with a value of 0.84, which is a high positive correlation.

Besides the similarity of the two trends, the lag which has been seen in the previous cases can be seen in Australia too. For example, the first NHUC peak is in 1989.2 and the first peak in the completion time is in 1990.1. The same pattern exists in the third quarter of 1994 where there is a peak point for NHUC and it is reflected after three quarters in completion time. Additionally, at the beginning of 2001, there is a trough in NHUC. This is also followed by a trough in the completion time at the end of this year.

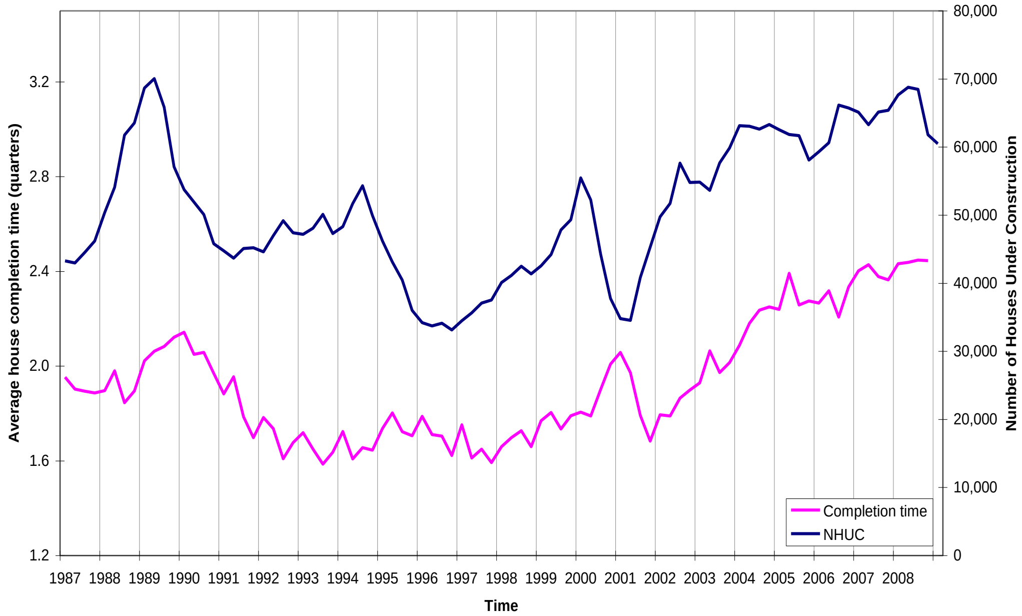


Figure 4-23: Number of houses under construction and average house completion time in Australia

Section summary

This part of the research has been dedicated to the investigation of the probable correlation between the average house completion time and the number of houses under construction. This correlation is suggested by the workflow-based planning approach. In this regard, two parameters of average house completion time and number of houses under construction have been drawn against each other and compared.

This analysis has been undertaken for Australia and five of its states: Victoria, Western Australia, New South Wales, Queensland and South Australia. As a result, a strong correlation between the average house completion time and number of houses under construction appeared in the graphs and the validity of the workflow-based planning approach in the house building industry has been demonstrated.

It has also been shown that there is a lag between the trend of number of houses under construction and average house completion time. This lag is discussed in the next chapter. Figure 4-24 summarizes all the above graphs in one place. The NHUC-completion time correlation can be clearly seen in these graphs.

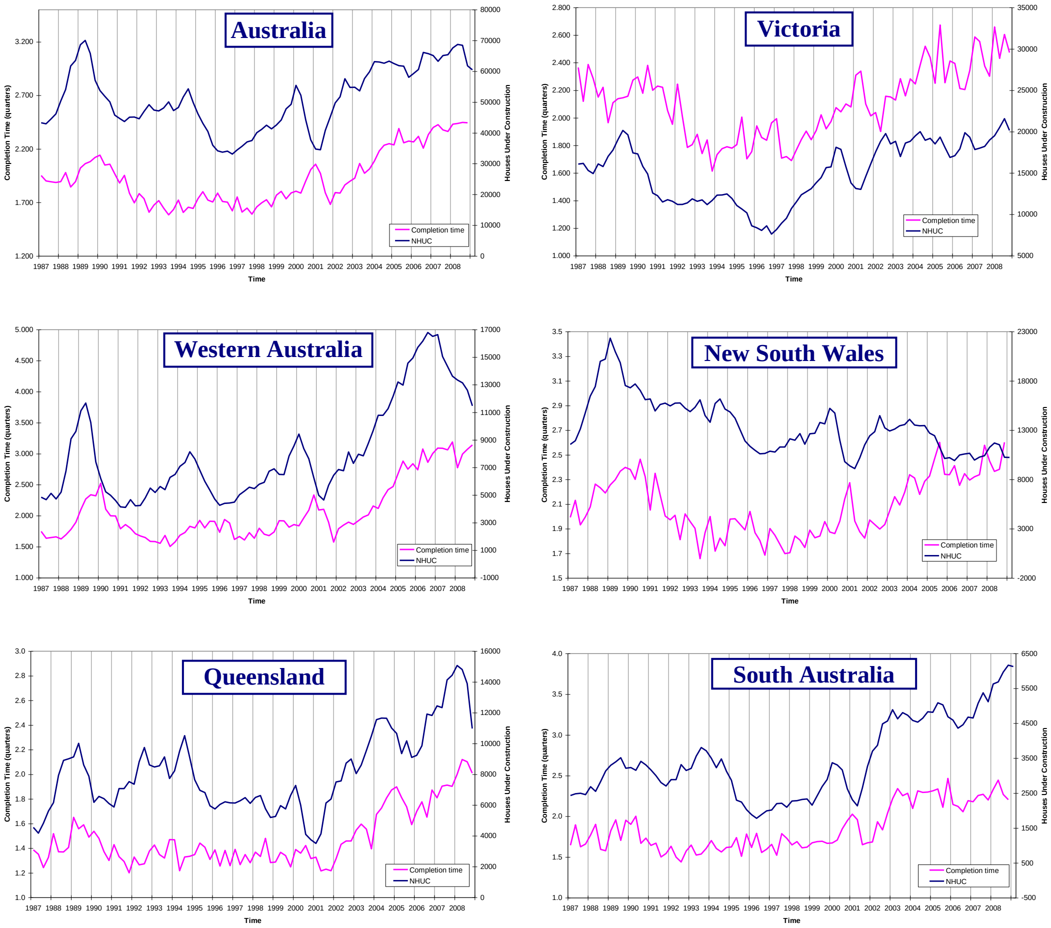


Figure 4-24: Number of houses under construction and average house completion time in Australia and different states

4.4 Chapter Summary

The Australian house building industry has seen an increase in the average house completion time since 2000. This research has used two planning approaches to explain this: 1) activity-based planning approach and 2) workflow-based planning approach. It has investigated the shortcomings of the activity-based planning approach and the potency of the workflow-based planning approach in explanation of changes in average house completion time in Australia.

In this regard, the effect of production rate, project scope and the number of houses under construction on average house completion time have been studied. The first two are proposed by the activity-based planning approach as effective parameters on completion time, and the last parameter is proposed by the workflow-based planning approach.

Quarterly number of house completions has been used as the proxy for production rate of the house building industry. The analysis has shown no apparent association between production rate and average house completion time in the State cases of Victoria, Western Australia, Queensland, South Australia and the meta case of Australia. The only state that has shown the association was New South Wales. In this state, the production rate has been declining since 2000. This decline made the completion time longer during this period.

In the case of Australia and other states, because the increasing trend of average house completion time has taken place during the time that production rate has been relatively constant, it can be concluded that this increase has not been caused by the loss in production rate as is suggested by the activity-based planning approach.

The other parameter suggested by this approach is project scope. The effect of this parameter on average house completion time was studied using the trend of average house floor area. This trend also showed that the reason for the increase in the average house completion time is not the increase in project scope. South Australia is the strong refuting case in this matter where the average house floor area has declined since 2000 while the completion time has consistently increased.

The next parameter that was investigated in this chapter was the number of houses under construction. This parameter is suggested by the workflow-based planning approach as an influencing factor on completion time. The study of the trend of this parameter has shown a strong correlation with average house completion time. This correlation has been verified in all the state cases and the meta case.

Although the correlation between number of houses under construction and average house completion time is dominant in the period of study, there are some cases in which the average house completion time does not follow the trend of number of houses under construction. These cases have been seen in New South Wales, Queensland and South Australia for short periods. Therefore, the workflow-based planning approach was used for the explanation of this inconsistency. This approach suggests that this inconsistency is because of changes in the production rate. Thus, the trend of production rate using number of house completions was investigated.

It has been shown that whenever the inconsistency between average house completion time and number of houses under construction occurs, there is a change in production rate. It was demonstrated that when production rate is consistent, the completion time is clearly influenced by number of houses under construction. But when production rate changes, the completion time is affected by this change and both the number of houses under construction and production rate should be considered in explanation of the industry's behaviour.

This chapter began with a concern about the recent increase in average house completion time in Australia. It was described that the main reason for this increase is the growth of the number of houses under construction. It was also demonstrated that the workflow-based planning approach has a potential in explanation of the house building industry's dynamics in relation to house building completion time. Therefore, the following chapters take this approach and investigate further the house completion time and the implications of work-flow based planning.

This chapter focused on the correlation between average house completion time, number of house completions, and number of houses under construction. The next chapter continues these attempts by investigating the relationship between these parameters. It takes the workflow-based planning approach and investigates applications in the house building industry.

5 CHAPTER FIVE - WORKFLOW-BASED ANALYSIS OF HOUSE COMPLETION TIME IN AUSTRALIA

5.1 Introduction

The previous chapter showed that there is a strong correlation between number of houses under construction (NHUC) and average house completion time in the Australian house building industry. This correlation is, in fact, suggested by the workflow-based planning approach. Therefore, it was concluded that the workflow-based planning approach offers a better explanation for the house building industry's dynamics than the activity-based planning approach. Further, it was demonstrated that the correlation between the number of houses under construction and average house completion time can be affected by the number of house completions in the industry. This is an aspect that can also be explained by the workflow-based planning approach.

Workflow-based planning approach does not only talk about the correlation between number of houses under construction and completion time. This approach also covers the effect of production rate - number of house completions - on average house completion time and relates all these three parameters in Little's law. However, the applicability of this law in the house building industry needs to be verified. This chapter investigates the validity of this approach by verifying Little's law in the house building industry.

The chapter commences with an explanation of Little's law. Then a description of how it was adapted for house building industry is provided. The result is a hypothetical relationship between average house completion time, number of houses under construction, and number of house completions. According to the research design, this relationship is examined through five state cases studies and one national case and the result is reported at the end of each case, as well as at the end of each section.

The case studies in this part of the research are the same cases used in Chapter four. Victoria, Western Australia, Queensland, New South Wales and South Australia are the state case studies and Australia is the national case.

5.2 Little's law applicability

Little's law was described in Chapter two (Section 2.3.2). It was explained that this law explains the relationship between the work in process (WIP), cycle time (CT) and throughput (TH) in a production line (Hopp and Spearman, 2008). Workflow-based planning approach in construction adopted this law from production planning and implemented it in construction projects. This section extends this adoption to the house building industry and investigates the applicability of the law in the explanation of changes in Australian average house completion time.

However, since Little's law is developed for manufacturing systems, it needs to be adapted for the house building industry. Therefore, this part of study starts with this adaptation and then the multiple-case studies are examined for applicability of the law.

5.2.1 Little's Law for the house building industry

Little's law is the fundamental law explaining the relationship between WIP, cycle time and throughput. In house building where houses are the products of the system, WIP is measured by number of houses under construction (NHUC), cycle time is measured by average house completion time (AHCT), and number of house completions (NHC) is the throughput of the system.

With these definitions, Little's law for the house building industry would be as follows:

Little's law in manufacturing: $WIP = CT * TH$ *Equation 5-1*

$$
\text{Substitutions:} \quad \begin{array}{l} WIP \rightarrow NHUC \\ CT \rightarrow AHCT \\ TH \rightarrow NHC \end{array}
$$

$\Rightarrow$ *Little's law for house building:* $NHUC = AHCT * NHC$ *Equation 5-2*

It should be noted that house completion time is influenced by the NHUC at the construction commencement of a house. For example, if a house starts in the first quarter of a year, the NHUC which affects this house is reported within that quarter. The completion of this house, and its completion time, are reported when it is completed, which may be in the third quarter. It means the AHCT and NHC reported in the third quarter are associated with the NHUC of the first quarter. This is the reason for the lag observed in Chapter four between NHUC graphs and AHCT graphs.

This lag adds the effect of time to Little's law presented above. This point is presented mathematically as follows:

$$NHUC_{(t)} = AHCT_{(t+l)} * NHC_{(t+l)}$$ *Equation 5-3*

Where l in the term $t+l$ represents the lag and has the same dimension as AHCT. Since the AHCT varies, finding the best l for Little's is part of this analysis.

To clarify how l affects the analysis and how it has been considered in this research, a part of the numerical data in Appendix A is presented in Table 5-1.

Table 5-1: Selected data from Appendix A for illustrative purposes

Time	NHUC	AHCT	NHC
1987.1	43,297	1.953	20,344
1987.2	42,968	1.903	22,102
1987.3	44,531	1.894	21,867
1987.4	46,179	1.887	24,699
1988.1	50,381	1.896	20,982
1988.2	54,081	1.980	25,204

Table 5-1 is a selection of data derived from ABS (2009) tables. In this table, the data for each parameter is reported at the end of the quarter. For example, the data related to 1987.4 (highlighted in Table 5-1) are the data reported at the end of the fourth quarter of 1987. However, as explained above, the NHUC in this quarter does not affect the houses which are being completed in this quarter. NHUC affects the houses that are started in this quarter and will be finished in 1.98 quarters (AHCT reported at 1988.2). It means the NHUC reported in 1987.4 is related to the AHCT and NHC reported in 1988.2.

5.2.2 The verification of Little's law applicability

The applicability of Little's law that shows the relationship between average house completion time, number of houses under construction, and number of house completions in the Australian house building industry, is the second objective of the thesis (Section 3.2). However, this relationship is a hypothesis that needs to be verified and the verification is undertaken according to the research design on all the cases studies.

The verification in each case study is made by the comparison of the actual and predicted NHUC. The time series for all three parameters of NHUC, AHCT and NHC are available (Appendix A). Thus, if NHUC is predicted by the law and compared with the actual data, the level of errors would show the validity of the law in the industry. In other words:

$$\left.\begin{array}{l} NHUC_{pred(t)} = AHCT_{act(t+l)} * NHC_{act(t+l)} \\ \\ NHUC_{act(t)} \textit{ is available from ABS database} \end{array}\right\} \Rightarrow \text{Comparison of } NHUC_{pred} \text{ and } NHUC_{act} \text{ would show applicability of the law}$$

Equation 5-4

The comparison in this research is made using three methods. The first method is to use the error metrics, which show the level of errors between prediction and the actual data. The second method is the use of r-square, which shows the strength of the relationship between the actual and predicted data. The third method is the drawing of the trend of actual and predicted data in the same graph to make a visual comparison.

Error metrics

The error in a forecast is the deviation of predicted data from actual data. To analyse the accuracy of a forecast there are some error metrics that quantitatively compare the predictions with the actual observations. Three metrics that are commonly used are the mean absolute deviation, mean square error, and mean absolute percentage error (Evans, 2010).

The mean absolute deviation (MAD) is the average of the deviation between the actual and the predicted data:

$$MAD = \frac{\sum_{t=1}^{n} |A_t - P_t|}{n}$$ *Equation 5-5*

Where A_t is the actual data for the time *t*, P_t is the predicted data for the time *t* and *n* is the number of forecast data. In the case of this research MAD is:

$$MAD = \frac{\sum_{t=1}^{n} |NHUC_{act(t)} - NHUC_{pred(t)}|}{n}$$ *Equation 5-6*

Mean square error (MSE) is the error metric, which penalises larger errors by squaring them. The formula for MSE is as follows:

$$MSE = \frac{\sum_{t=1}^{n} (A_t - P_t)^2}{n}$$ *Equation 5-7*

The MSE in this research is:

$$MSE = \frac{\sum_{t=1}^{n} (NHUC_{act(t)} - NHUC_{pred(t)})^2}{n}$$ *Equation 5-8*

The metrics of MAD and MSE use the scale of the time series data. They are the metrics for the comparison of different predictions. Therefore, this research uses them only for the comparison of different predictions and sensitivity analysis.

Mean absolute percentage error (MAPE) is the average of the absolute error divided by the actual data. This metric does not have a scale and can show the accuracy of a prediction regardless of its scale.

$$MAPE = \frac{\sum_{t=1}^{n} \left| \frac{A_t - P_t}{A_t} \right|}{n} \times 100$$ *Equation 5-9*

For this research:

$$MAPE = \frac{\sum_{t=1}^{n} \left| \frac{NHUC_{act(t)} - NHUC_{pred(t)}}{NHUC_{act(t)}} \right|}{n} \times 100$$ *Equation 5-10*

r-square

The second method of comparison, r-square, provides information about the strength of the relationship between the prediction and the actual time series. Its value is between 0 and 1. A value of 1 indicates a perfect fit and a strong relationship, and a value of 0 indicates that no relationship exists (Evans, 2010). This parameter also shows the similarity between the trend of the predicted and actual time series.

The relationship between prediction and the actual time series is different from the accuracy of the prediction. The relationship shows how precisely the behaviour of a phenomenon is predicted. The relationship is about the prediction of the increase and decrease in trends. This fact is explained more precisely in the actual cases of the research.

The r-square can be calculated by statistical software. This study used Minitab for this purpose.

Visual comparison

The third method to test the prediction accuracy is visual comparison. The trend graph of the actual data and the result of Little's law are drawn on the same figure. This stage of the verification is done with the best parameters found for Little's law. The closeness of the prediction and the actual data shows the applicability of the law in the house building industry.

5.2.3 Applicability of Little's law in the house building industry

The following sections encompass the result of the verification of Little's law in the Australian house building industry. The time span for this research is the 20 years since 1987. Six cases have been selected for this study, including one case at the national level and five cases at the state level.

Following sections are the result of the analysis on these cases.

Victoria

Prediction of the number of houses under construction needs the actual data of the industry's number of house completions and average house completion time (Equation 5-4). These data have been obtained from ABS (2009) reports and can be found in Appendix A. The Victorian average house completion time has been presented in Chapter four (Figure 4-15). Figure 5-1 in this chapter shows the trend of the actual number of house completions in Victoria.

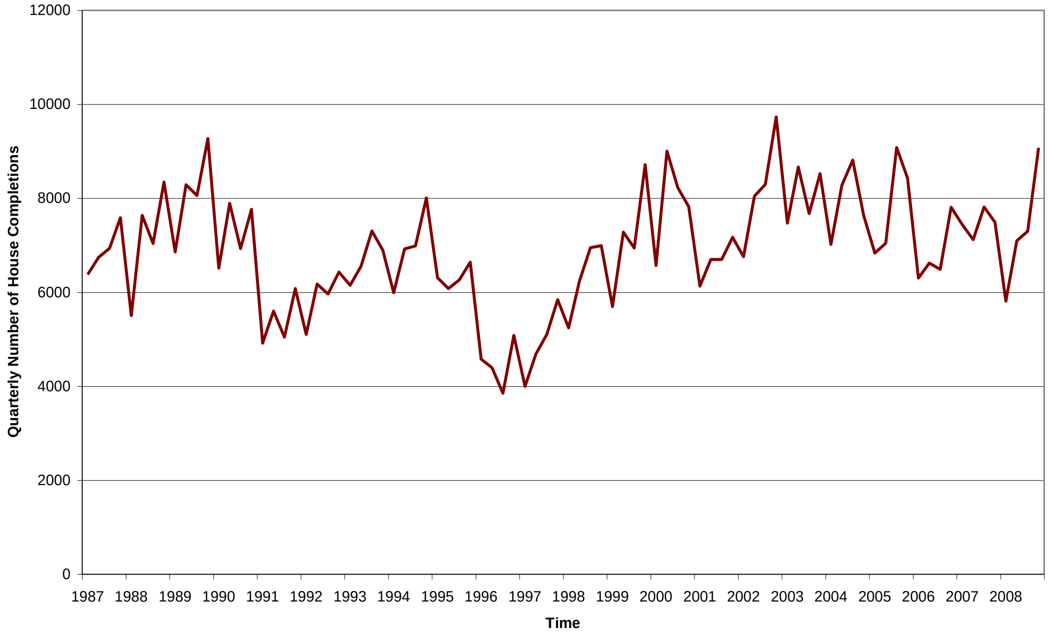


Figure 5-1: Quarterly number of house completions in Victoria

$NHUC_{pred}$ **and** $NHUC_{act}$ **comparison using r-square:** the prediction of NHUC can be made with different lags. The AHCT time series for the Victorian house building industry is between 1 and 3 quarters. The mean and mode AHCT are 2.1 and 2.22 quarters respectively. The analysis is undertaken with two and three quarters lag and the result is compared.

Using Little's law, the predicted number of houses under construction and the related error metrics are calculated. The following table shows these metrics and the accuracy of the prediction.

Table 5-2: The error metrics for the predicted NHUC in Victoria

Lag	MAD	MSE	MAPE
two quarters	1,377	2,908,593	9.64
three quarters	1,536	3,777,112	10.92

As was explained in Section 5.2.2, the error metrics can help the comparison between different predictions. The one with the smaller values of the errors is the better prediction. Therefore, as can be seen in Table 5-2, the two-quarter lag is better than the three quarter lag and is highlighted in this table.

The MAPE for this prediction is 9.64 percent. This shows the average of error percentage is less than 10 percent, which is an acceptable error for the prediction of an industry.

$NHUC_{pred}$ ***and*** $NHUC_{act}$ ***comparison using r-square:*** The r-square between the predicted and actual data shows their relationship. In other words, it shows how the prediction conforms to the reality. The r-square analysis is undertaken and table 5-3 summarizes the result of this analysis.

Table 5-3: The r-square of NHUC predictions for the Victorian house building industry

Lag	R-square
two quarters	79%
three quarters	73.5%

The r-square reported in Table 5-3 is acceptable for the prediction. Together with the error metrics, r-square is the second evidence of the applicability of Little's law in the Victorian house building industry. Table 5-3 shows a higher r-square for the two-quarter lag which supports the result of the error metrics in the previous section. The next step is the visual comparison.

$NHUC_{pred}$ **and** $NHUC_{act}$ **comparison using Visual comparison:** In this step the trends of the predicted and the actual number of houses under construction are drawn on the same graph to provide a visual comparison between these two time series.

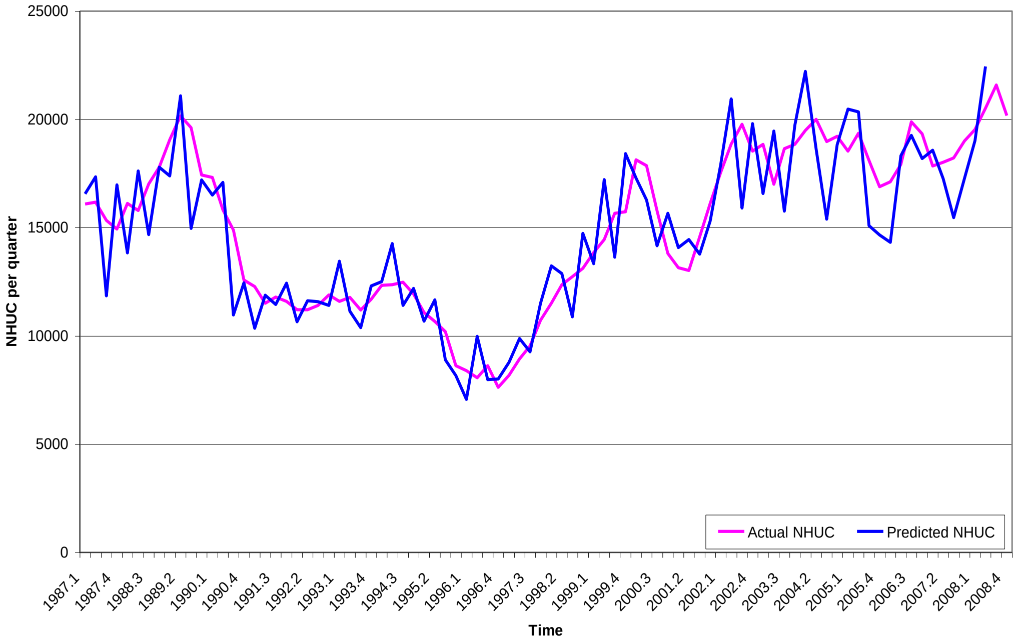


Figure 5-2: Visual comparison between predicted and actual number of houses under construction in Victoria

As illustrated in Figure 5-2, these two graphs are very close. The behaviour of the actual data is exactly predicted by Little's law and there is a very small difference between the two graphs. However, it seems the predicted data fluctuate around the actual data and, therefore, the elimination of the fluctuation might improve the prediction.

The reason for this fluctuation is due to the fluctuation of the actual number of house completions (Figure 5-1). The data used for number of house completions are the original number of completions reported by ABS (2009). These original data can be made smoother with statistical methods such as moving average.

Number of house completions moving average: To smooth out the NHC time series and remove its seasonal fluctuations, a simple moving average is used. Use of a moving average is normal within housing research (Joiner et al., 2009, National Housing Supply Council, 2010a). The averaging process cancels the extreme fluctuations and the result is a smooth series. This smoothed series is closer to the trend of the whole time series than the actual data.

The moving average can be obtained with different lengths, which indicate the number of data in each subset. In order to find the best length for the moving average, the Minitab software was employed. The best length for moving average is the one with the smallest value for the mean absolute percentage error (MAPE), mean absolute deviation (MAD) and mean square deviation (MSE). All these parameters are calculated using the software and are reported in table 5-4.

Table 5-4: The error metrics for finding the best number of house completions moving average

	Length			
Quarters	2	3	4	5
MAPE	12	13	12	13
MAD	817	881	815	849
MSE	1,008,275	1,138,445	984,499	1,098,030

As can be seen from Table 5-4, the best moving average is obtained with a length of four quarters. The moving average of number of house completions for the Victorian house building industry is shown in Figure 5-3.

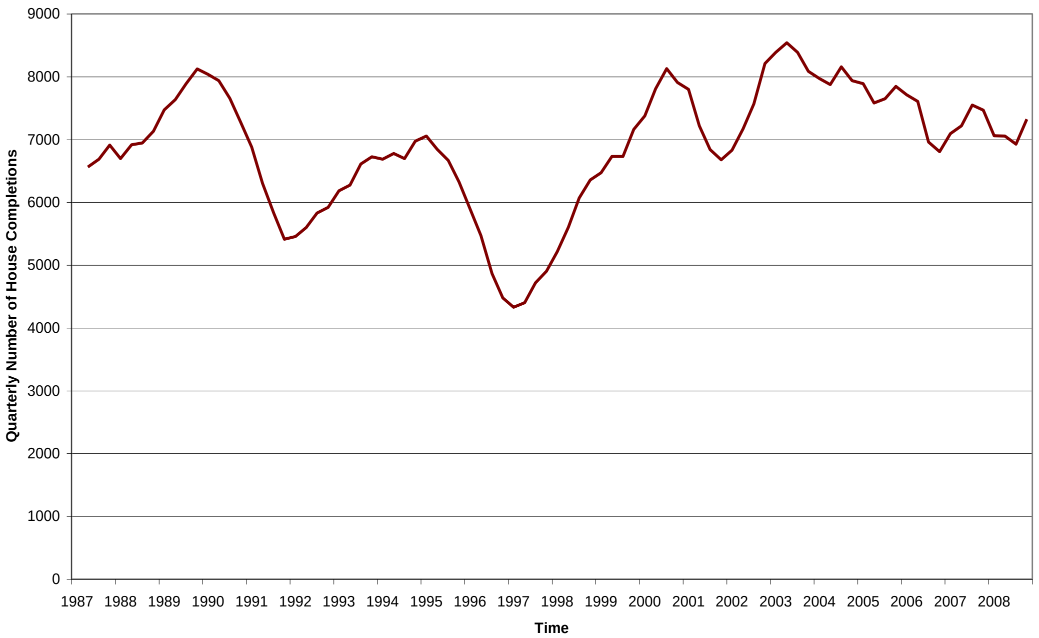


Figure 5-3: Moving average of the number of house completions with length 4 for Victoria

Now that the moving average for number of house completions is calculated, the analysis of the applicability of Little's law is repeated for the Victorian house building industry. However, this time the original number of house completions is replaced by the moving average time series.

Error metrics and r-square using number of house completions moving average: The same method of analysis has been applied using the moving average data. The following table shows the error metrics and r-square for the predictions based on the new analysis. The result of the use of number of house completions in the original data is also reported in this table to make possible the comparison between the result of the moving average and the original data.

Table 5-5 clearly shows that the use of the moving average for number of house completions, instead of the original data for number of house completions, leads to better results. As was explained earlier, the MSE metrics exaggerate the deviation from the actual data and, therefore, the extreme deviations are highlighted. Table 5-5 shows that there is a significant difference between MSE using moving average and using original data.

Table 5-5: Error metrics and r-square using moving average for number of house completions

	Using original number of house completions				Using number of house completions moving average			
Lag	MAD	MSE	MAPE	R-square	MAD	MSE	MAPE	R-square
two quarters	1377	2,908,592	9.64	79%	851	1,145,650	5.77	91.6%
three quarters	1536	3,777,112	10.92	73.5%	760	869,126	5.23	93.7%

The smallest error is produced by moving average for the number of house completions and two quarters lag. This error is 5.23% (MAPE). r-square also shows a strong relationship between the actual and the predicted data. According to this analysis, the prediction can be improved with the use of the moving average. This method is therefore, used for remaining cases of the study.

Visual comparison using moving average for number of house completions: Following that the error metrics and r-square showed an improvement in prediction, the visual comparison with the use of moving average for number of house completions is demonstrated in Figure 5-4.

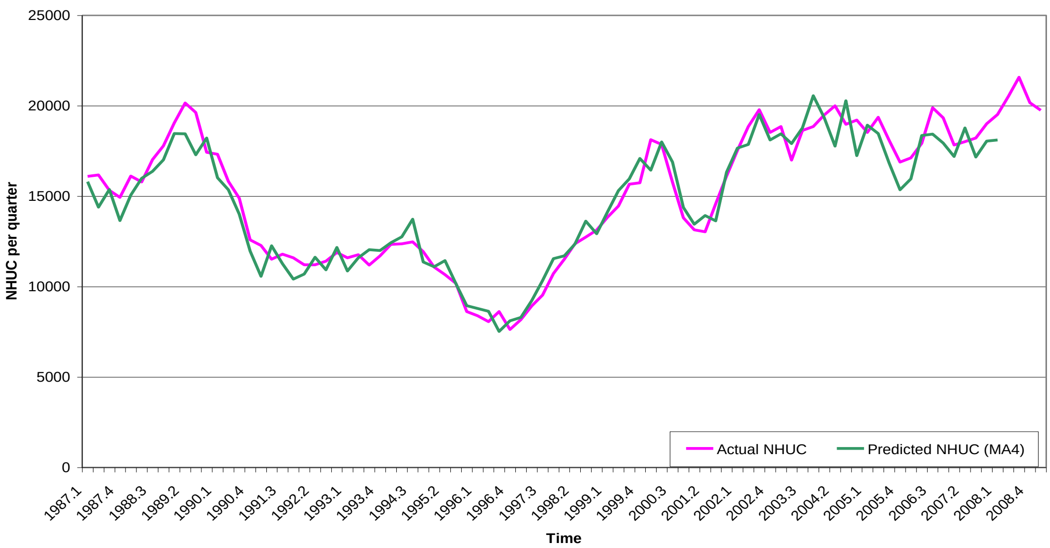


Figure 5-4: The comparison between predicted and actual NHUC using number of house completions moving average in Victoria

A comparison between Figures 5-2 and 5-4 clarifies the improvement made by the use of the moving average. As shown in Figure 5-4, the predicted NHUC is very close to the actual data. This conformity shows the strength of Little's law in prediction of the behaviour of the industry.

Applicability of Little's law in the Victorian house building industry: The applicability of Little's law was shown with the use of error metrics, r-square and visual comparison. According to this analysis, the number of houses under construction can be predicted by Little's law with 5.23% error. The strength of the relationship between the predicted and the actual number of houses under construction was also demonstrated with an r-square of 0.94. Likewise, the visual comparison showed the conformity of these two time series.

According to these comparisons, it can be concluded that Little's law is applicable in this case study at the state level. The lag that should be considered for Little's law in this case is three quarters. Therefore, the mathematical representation of the law in Victoria is as follows:

$$NHUC_{(t)} = AHCT_{(t+3)} * NHC_{(t+3)} \qquad \text{Equation 5-11}$$

Because Victoria was the first case study in this analysis, it was used as a pilot for the other cases. It was shown that the moving average of number of house completions leads to significantly better results. Therefore, the moving average is also used in other cases and its result is compared with the use of the original data.

The following section similarly analyses the Western Australia house building industry.

Western Australia

The same method that was used for Victoria is used for Western Australia. The best moving average is found using error metrics and then the NHUC is predicted using Little's law. The predicted data are compared with actual data and the level of errors is found by error metrics and r-square. If this level of error is acceptable, it is concluded that Little's law holds in this state.

The best length for moving average of number of house completions: As was explained in the previous cases, the smallest values for MAPE, MAD and MSE determine the best length for the moving average. The result of this analysis is shown in Table 5-9.

Table 5-6: The error metrics for finding out the best moving average length

	Length			
	2	3	4	5
MAPE	12	13	13	14
MAD	448	498	478	528
MSE	300834	369873	362776	438913

Table 5-6 shows that the best length for moving average is two. This length is used for further studies on this case.

$NHUC_{pred}$ and $NHUC_{act}$ comparison using error metrics: The comparison between $NHUC_{pred}$ and $NHUC_{act}$ shows the strength of the prediction and consequently the applicability of Little's law. The error metrics show the accuracy of this comparison. These metrics measure the errors made by Little's law in prediction of the house building industry's behaviour.

The average and mode of AHCT time series are 2.07 and 1.64 quarters. Therefore, the lag of two and three quarters was considered in this analysis. The following table includes the error metrics made by Little's law in Western Australia.

Table 5-7: The error metrics indicating the accuracy of the predictions in Western Australia

	Using original number of house completions			Using number of house completions moving average		
Lag	MAD	MSE	MAPE	MAD	MSE	MAPE
two quarters	853	1,246,869	10.48	607	545,984	7.84
three quarters	973	1,503,916	11.98	657	677,734	8.83

The smallest metrics are the result of the use of number of house completions moving average and with two quarters lag. Little's law in this state predicts the NHUC with 7.84% error (MAPE) which is an acceptable error for prediction of an industry.

$NHUC_{pred}$ and $NHUC_{act}$ comparison using r-square: The error metrics showed a strong and accurate prediction. However, r-square is used to show the relationship between the predicted and actual data. The following table comprises the r-square parameter between different predictions using Little's law and actual data. Although it was shown in other cases that the moving average makes a better prediction than the original data, the analysis with original data also was undertaken.

Table 5-8: The r-square for different predictions using Little's law

Lag	Original number of house completions	Number of house completions moving average
two quarters	90.5%	96.7%
three quarters	88%	95.7%

The comparison between the result of moving average for number of house completions and original data for number of house completions confirms the use of moving average for prediction. The best lag is two quarters which is consistent with the result of error metrics analysis. Further, r-square of 96.7% shows a strong relationship between the predicted and actual data.

$NHUC_{pred}$ ***and*** $NHUC_{act}$ ***comparison using visual comparison:*** The error metrics and r-square reported in Tables 5-7 and 5-8 demonstrated the strength of the prediction by the use of Little's law. The best prediction is made by the moving average and with two quarters lag. Therefore, the visual comparison is made based on these results.

The visual investigation of the comparison between predicted and actual NHUC needs both graphs in the same figure. Thus, these graphs were drawn in the same figure and the result is shown in Figure 5-5.

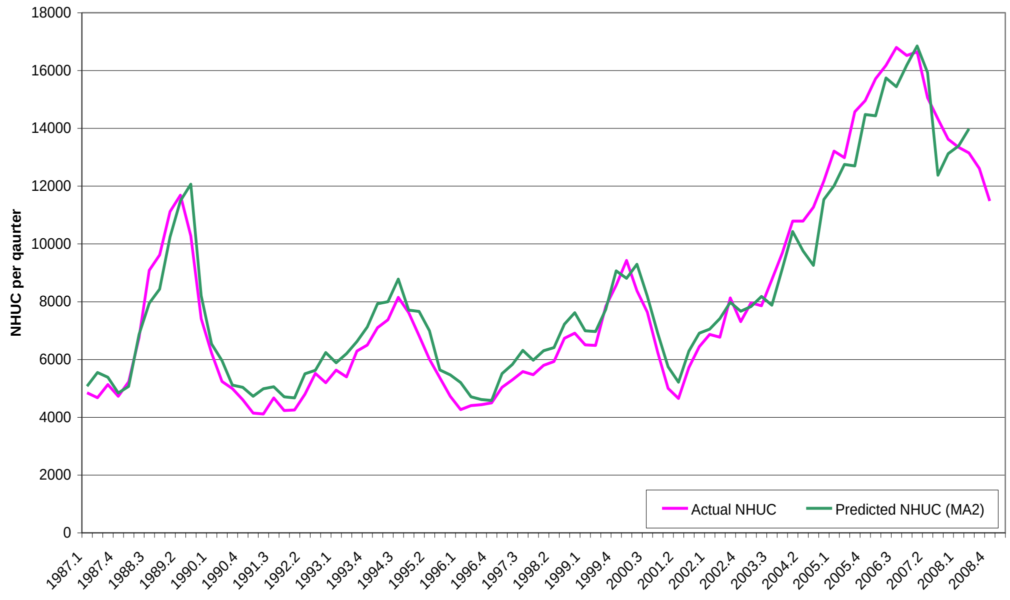


Figure 5-5: The comparison between predicted NHUC and actual NHUC in Western Australia

This figure demonstrates that the number of houses under construction is precisely predicted by Little's law. The closeness of these two graphs shows the strength of the prediction and the law's applicability in the Western Australia house building industry.

Applicability of Little's law in the Western Australia house building industry: It was shown in Table 5-7 that the best prediction makes only 7.84% error (MAPE equals to 7.84%). Figure 5-5 further demonstrated the conformity of the predicted and actual NHUC, and r-square of 96.7% proved the strength of the prediction in forecasting the trend of the industry. All these demonstrate the applicability of Little's law in this case. Further, the lag proposed by this analysis was two quarters. Therefore, Little's law for this state is as follows:

$$NHUC_{pred(t)} = AHCT_{act(t+2)} * NHC_{act(t+2)} \qquad \textit{Equation 5-12}$$

Western Australia is the second case that shows the applicability of the law in the Australian house building industry. The remaining state cases are South Australia, New South Wales and Queensland. These states are the subjects of the following sections.

South Australia

South Australia is the third case in the investigation of Little's law applicability in the house building industry. Similar to other cases, the first step is to find the best moving average for the number of house completions. Calculation is then undertaken of different predictions using Little's law and their comparisons with the actual data.

The best length for moving average of number of house completions: It was shown in the previous cases that the use of moving average of the number of house completions is better than the original data. Therefore, the moving average of the number of house completions using different lengths is calculated and the best length is selected using the error metrics. Following table shows the results of this analysis.

Table 5-9: The error metrics for finding the best length for moving average in South Australia

	Length		
	2	3	4
MAPE	10.4	11.0	11.2
MAD	190.8	199.6	201.9
MSE	52,429	63,123	63,169

As can be seen in Table 5-9, the moving average with length of two produces the lowest MAPE, MAD and MSE. Therefore, this length is used for further studies

$NHUC_{pred}$ ***and*** $NHUC_{act}$ ***comparison using error metrics:*** Table 5-10 comprises the error metrics for different predictions using Little's law. The lags for the prediction of NHUC are two and three quarters. These values of lag are selected because the AHCT time series in this state has the average and mode of 1.85 and 1.69 quarters.

Table 5-10: The error metrics indicating the accuracy of the predictions

	Using original number of house completions			Using number of house completions moving average		
Lag	MAD	MSE	MAPE	MAD	MSE	MAPE
two quarters	360	203,531	10.32	231	80,055	6.90
three quarters	356	216,638	10.21	252	111,918	7.54

This table demonstrates that the best prediction is made by the use of moving average and the lag of two quarters. This prediction undertaken by Little's law produces 6.9% error.

The comparison between the results of moving average and original data once more shows the advantage of the use of moving average. Moving average makes smaller errors and better predictions for each of these three criteria.

As was mentioned earlier, the average and mode house completion time are 1.85 and 1.69 quarters. With these average and mode, the lag in Little's law is expected to be two quarters. The result of the analysis in this section verifies this fact where the errors using two quarters lag are smaller than the errors made by three quarters lag.

$NHUC_{pred}$ ***And*** $NHUC_{act}$ ***comparison using r-square:*** The next step is to investigate the relationship between the predicted and the actual data. The strength of this relationship is measured by r-square. This r-square is calculated and the result is reported in the following table.

Table 5-11: The r-square for different predictions using Little's law

Lag	Original number of house completions	Number of house completions moving average
two quarters	82%	93.8%
three quarters	81.5%	91.2%

The best r-square in this case is 93.8%, which is a high r-square and is evidence of the applicability of Little's law in the South Australia house building industry. Table 5-11 shows that the best prediction is made by the moving average and with two quarters lag. This result is consistent with the result of error metrics.

$NHUC_{pred}$ and $NHUC_{act}$ comparison using visual comparison: To see the conformity of the predicted NHUC and the actual NHUC, these two graphs are drawn in Figure 5-6. Note that the predicted graph is calculated based on the result of the previous sections. In this prediction the lag is two quarters and the moving average is used.

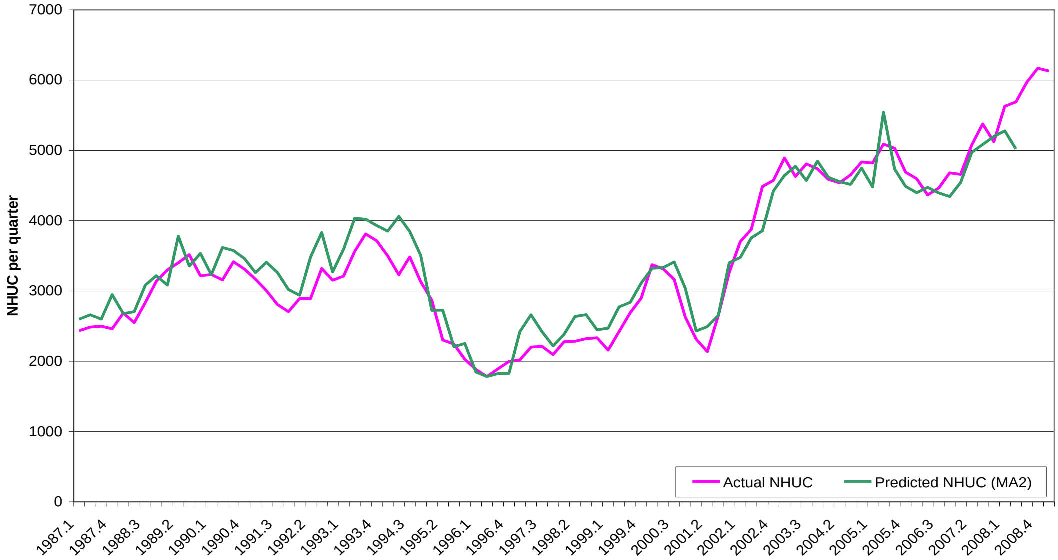


Figure 5-6: The comparison between predicted NHUC and actual NHUC in South Australia

As illustrated in this graph, the predicted and the actual NHUC are very close. The peaks and troughs happen at the same time and the trends are similar. This conformity once more proves the applicability of Little's law in the house building industry.

Applicability of Little's law in the South Australia house building industry: The error metrics showed 6.9% error in prediction and r-square of 93.8% demonstrated a strong relationship between the predicted and actual data. The applicability of Little's law was also visually illustrated through the comparison between the results of the law and the actual number of houses under construction. Considering these comparisons, it is concluded that Little's law is applicable in the South Australia house building industry.

Based on the lag proposed by the best prediction, Little's law for this state is as follows:

$$NHUC_{pred(t)} = AHCT_{act(t+2)} * NHC_{act(t+2)} \quad \text{Equation 5-13}$$

South Australia is the third case, which confirms this applicability. Following sections include two more states and a national case.

New South Wales

In the previous chapter, it was shown that New South Wales was the only case where the increase of completion time since 2000 could not be explained by the trend of number of houses under construction and was explained by the loss of number of house completions. However, the trend of average house completion time before year 2000 showed a correlation between this parameter and number of houses under construction. Thus, it was concluded that the house completion time is influenced by number of houses under construction as well as number of house completions. This conclusion is in compliance with Little's law.

Little's law is in fact the precise explanation of the relationships between these three parameters of average house completion time, number of houses under construction, and number of house completions. This law indicates how the average house completion time is influenced by number of houses under construction as well as number of house completions and determines the significance of this influence.

However, the applicability of the law in the house building industry is not proven yet and New South Wales is the fourth case in this study for the verification of its applicability. For this purpose the same method that was used for previous cases is employed this case. The first step is to find the best length for moving average of number of house completions and then the comparison between the result of Little's law and the actual data is accomplished.

The best length for moving average of number of house completions: Table 5-12 is the result of the analysis on finding the best length for the moving average for number of house completions.

Table 5-12: The error metrics for finding out the best length for moving average length in NSW

	Length			
	2	3	4	5
MAPE	12	13	12	13
MAD	689	734	684	737
MSE	789,068	881,470	798,009	938,851

As can be seen in this table, the length of two makes the smallest value for MAPE, MAD and MSE. Therefore, this length is used for calculation of moving average in further studies.

$NHUC_{pred}$ and $NHUC_{act}$ comparison using error metrics: The error metrics between the predicted and the actual number of houses under construction are calculated and the result is shown in the following table. The analysis is done for two and three quarter lag. This is based on the AHCT series where the average and mode are 2.08 and 2.34 quarters respectively.

Table 5-13: The error metrics indicating the accuracy of the predictions in New South Wales

	Using original number of house completions			Using number of house completions moving average		
Lag	MAD	MSE	MAPE	MAD	MSE	MAPE
two quarters	1678	4,284,766	14.40	1427	3,119,764	11.66
three quarters	1795	5,053,498	15.38	1319	2,779,726	10.77

Table 5-13 demonstrates that the best prediction is made by the use of the moving average and with three quarters lag.

Finding the best results with the moving average is consistent with the previous cases. Using the moving average shows a considerable improvement compared to the use of original data. This improvement can be clearly seen with the predictions of three quarters lag where the original data makes 15.38% error and the moving average makes 10.77%.

Further, since the average and mode AHCT are bigger than two quarters, it is expected that the lag between the cause of NHUC and effect of AHCT is more than two quarters. The result of the error metrics is consistent with this fact where it finds better predictions with three quarter lag.

The 10.77% error is acceptable for research on an industry. However, this level of error is slightly higher than previous cases. These errors are demonstrated visually in the visual comparison.

$NHUC_{pred}$ and $NHUC_{act}$ comparison using r-square: The next step is to find r-square between the predicted and the actual data. The result of this analysis is summarized in Table 5-14.

Table 5-14: The r-square for different predictions using Little's law

Lag	Original number of house completions	Number of house completions moving average
two quarters	68%	79%
Three quarters	59%	83%

According to this table, the best prediction is made by the moving average and with three quarters lag. This result is consistent with the error metrics analysis. Further, the effect of the use of moving average can be seen in this table. The r-square for the prediction using the original data and with three quarters lag is 59% while number of house completions moving average makes 83% r-square which is much higher than 59%. Although 83% r-square is an acceptable conformity between a prediction and actual data, it is lower than the r-squares in the previous cases.

$NHUC_{pred}$ ***and*** $NHUC_{act}$ ***comparison using visual comparison:*** It has been mentioned that although the errors and r-square analyses show the applicability of Little's law in this state, the predictions in this state are not as accurate as the previous states. This inaccuracy is clarified using the visual comparison. In this regard, the predicted and actual NHUC are drawn on the same figure. Following figure shows these two graphs beside each other.

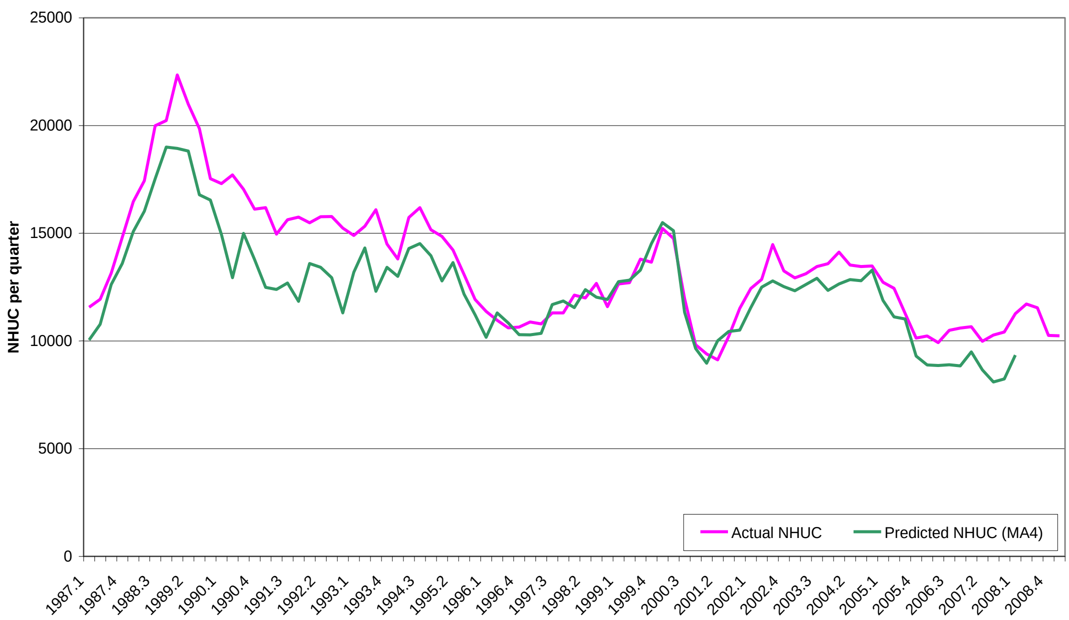


Figure 5-7: The comparison between predicted NHUC and actual NHUC in New South Wales

Figure 5-7 shows that the predicted NHUC is quite close to the actual one. The same trend as actual data is followed by the predictions. The timing for troughs and peaks is similar. However, NHUC is slightly under-estimated in the prediction. This underestimation was not seen in the previous cases and there is an inconsistency. According to replication logic, the inconsistency between cases can strengthen the argument if it is explained by the hypothesis under investigation.

The underestimation is made by Little's law and suggests that with this AHCT and NHC, the NHUC should be less than the numbers that are reported by ABS. This means, according to this law, there are houses under construction in this state that are reported by ABS as "under construction" but they are built by companies not registered in this state. This is an extra capacity which is influencing the NSW house building industry.

The geography of NSW shows this extra capacity might be coming from the northern border of this state (Figure 5-8). In the north of NSW, that there are towns and areas which are closer to Brisbane (the capital city of Queensland) than Sydney (the capital city of NSW). This might be the reason for the extra capacity coming from Queensland industry.

The existence of extra capacity is an explanation suggested by Little's law that complies with the geography of this state. However, if there is an extra house building capacity flowing from Queensland to NSW, then the same phenomenon should be seen in the analysis of Queensland house building industry reflected in a shortage of capacity. This analysis is done for Queensland in the next section and, therefore, the verification of this explanation is followed in that case.

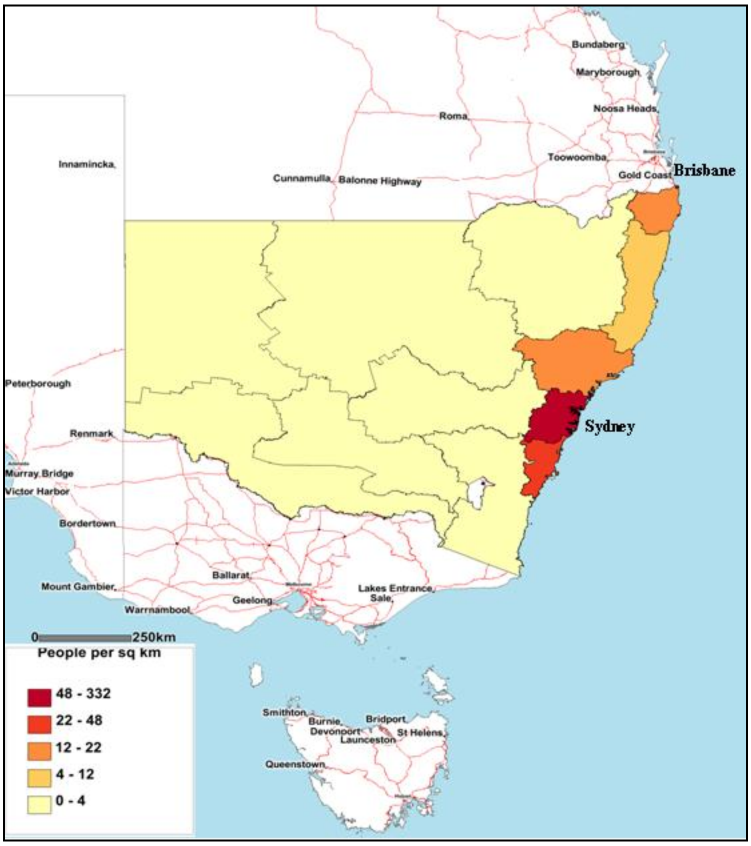


Figure 5-8: Population density map of New South Wales

Applicability of Little's law in the New South Wales house building industry: It was shown in Table 5-14 that the prediction of NHUC by Little's law has an r-square of 83% with actual NHUC. In addition, the error percentage made by this prediction was 10.77%. Figure 5-7 demonstrated the strength of the prediction. This prediction is slightly underestimated, which was explained using the law. The use of moving average for number of house completions was confirmed and the best prediction was made by three quarters lag. Considering this lag, Little's law for this state is as follows:

$$NHUC_{pred(t)} = AHCT_{act(t+3)} * NHC_{act(t+3)} \qquad \text{Equation 5-14}$$

The next case, which is the last case at state level, is Queensland.

Queensland

Previous sections showed that Little's law is applicable for four of Australia's states and Queensland is the last case at state level. The analysis starts with finding the best length for the moving average of NHC and continues with the prediction of NHUC and its comparison with the actual data.

The best length for the number of house completions moving average: This step was proven necessary for the analysis because the use of the moving average showed better results than the use of actual data in all the previous cases.

Table 5-15 shows the result of the investigation of the best length for the moving average of number of house completions. The length with the smallest value for MAPE, MAD and MSE is selected as the best length.

Table 5-15: The error metrics for finding out the best length for moving average length in Queensland

	Length			
	2	3	4	5
MAPE	15	15	15	16
MAD	946	931	901	980
MSE	1,404,158	1,440,621	1,301,004	1,498,557

According to Table 5-15, the best length for the moving average is two. This length is used for further studies where the number of house completions is used.

$NHUC_{pred}$ ***and*** $NHUC_{act}$ ***comparison using error metrics:*** The first step in the investigation of the accuracy of the prediction is the calculation of error metrics. Table 5-16 shows the result of this analysis.

Table 5-16: The error metrics indicating the accuracy of the predictions in Queensland

	Using original number of house completions			Using number of house completions moving average		
Lag	MAD	MSE	MAPE	MAD	MSE	MAPE
two quarters	1,743	4,453,442	18.22	1,492	2,931,417	16.56
three quarters	1,876	5,527,866	19.68	1,582	3,252,950	17.34

The average and mode AHCT for this state are 1.48 and 1.35 quarters. Therefore, the lag in Little’s law is expected to be two quarters. As can be seen in Table 5-16, the better results are obtained by two quarters lag, which is consistent with this expectation. Further, similar to other cases, the results of the moving average is better than the original data. The best prediction with the least error is with the use of the moving average for number of house completions.

According to this table the smallest error is 16.56% which is acceptable for the applicability of a theory in an industry. However, this level of error is higher than the errors in other cases. The source of this error is explained with the visual comparison between the predicted and the actual number of houses under construction.

$NHUC_{pred}$ ***and*** $NHUC_{act}$ ***comparison using r-square in Queensland:*** Following table shows the r-squares between predicted and accrual NHUC.

Table 5-17: The r-square for different predictions using Little's law in Queensland

Lag	Original number of house completions	Number of house completions moving average
two quarters	69.4%	86.6%
three quarters	62.3%	86.7%

Table 5-17 shows that the highest r-square which shows the lowest errors is obtained by the use of moving average and three quarters lag in Little's law.

The r-square of 86.7% is a high r-square, which shows a strong relationship between the predicted and the actual data. In other words, the trend of the actual data is precisely predicted by Little's law. This is contrary to the fact that the errors made by the prediction are higher than other states. The visual comparison clarifies this contradiction.

$NHUC_{pred}$ ***and*** $NHUC_{act}$ ***comparison using visual comparison:*** It was mentioned that errors between predicted and actual data in Queensland are slightly higher than the previous cases. On the other hand, r-square shows a strong relationship between the predicted and actual data. The visual comparison in this section investigates this contradiction. For this purpose, the predicted and actual data for NHUC are drawn in Figure 5-9.

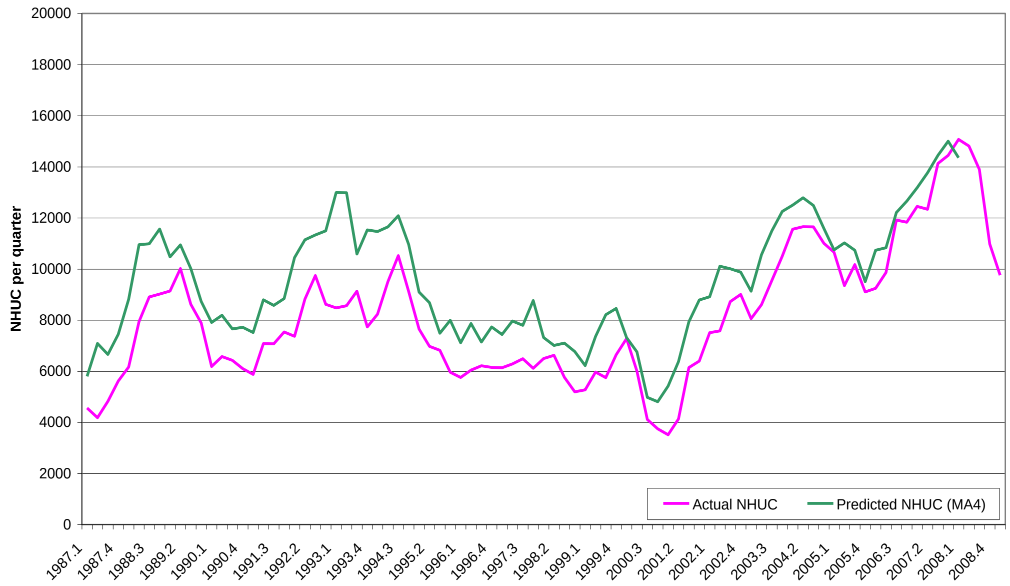


Figure 5-9: The comparison between predicted NHUC and actual NHUC in Queensland

As can be seen in this figure, the predicted graph has the same trend as the actual one. The peaks and troughs are similar and they occur at the same time. Any increase in the actual data is predicted by an increase in predicted data, and any decrease is predicted by a decrease. This is the reason for a high r-square and strong relationship between predicted and actual data. However, the prediction is overestimated. There is always a considerable error between these two graphs which results the errors reported in Table 5-16.

According to Little's law, the overestimation suggests that the number of houses under construction with this level of AHCT and NHC should be higher than the actual numbers. The Queensland house building industry works on higher number of houses than the numbers reported by ABS. In other words, part of the capacity of Queensland house building industry is engaged out of this state and is not reported as the NHUC for this state. This fact is consistent with the analysis of New South Wales industry which has shown an extra capacity. Therefore, Little's law could explain the inconsistency between these two cases and the previous cases and its validity is strengthened.

The remaining case is the meta case of Australia, which is analysed for the applicability of Little's law in the house building industry.

Australia

Australia is the meta case in this study that sums up all the previous cases and the remaining parts of the country. According to replication logic, the same steps as previous cases are followed for this case. These steps include finding the best moving average for the number of house completions, calculation of the predicted NHUC, and the comparison between the predicted and actual NHUC using error metrics, r-square and visual comparison.

The best length for the number of house completions moving average: It was shown in the previous cases that in the Australian house building industry, the use of moving average for the number of house completions produces better results. Therefore, the first step is to find the best moving average for the number of house completions in Australia. The best length for the moving average is indicated by the smallest MAD, MAPE and MSE. These parameters for different lengths are presented in the Table 5-18.

Table 5-18: The error metrics for finding out the best moving average length

	Length		
Quarters	2	3	4
MAPE	6	7	8
MAD	1,487	1,844	1,988
MSE	3,158,339	4,852,257	5,941,572

As demonstrated in the table, the minimum error is made by two quarters length for the number of house completions moving average. Therefore, the number of house completions time series is replaced by its moving average with the length of two quarters.

$NHUC_{pred}$ and $NHUC_{act}$ comparison using error metrics: Since the average and mode of the average house completion time in this case are 1.93 and 2.06 quarters, the lag between the time of NHUC and AHCT is expected to be two or three quarters. The analysis is undertaken for both of these lags and the best one is chosen as the best lag for prediction.

Similar to the previous cases, the first comparison is made by the error metrics. These metrics have been calculated and the result is reported in the following table.

Table 5-19: The error metrics indicating the accuracy of the predictions for Australia

	Using original number of house completions			Using number of house completions moving average		
Lag	MAD	MSE	MAPE	MAD	MSE	MAPE
Two quarters	3,821	23,676,164	7.66	2,137	7,022,090	4.24
Three quarters	4,431	31,638,011	8.87	3,366	16,310,819	6.78

Table 5-19 shows that the smallest error belongs to the prediction of two quarters lag with the use of moving average. The error percentage for this prediction is 4.24%. This level of error shows the strength of the prediction and the applicability of Little's law.

This case, like the previous cases, showed that the use of moving average for number of house completions is better than that for the original data. However, even the original data has an error of 8.87%, which is still adequate for prediction.

$NHUC_{pred}$ and $NHUC_{act}$ comparison using r-square: The r-square analysis is done for the verification of Little's law applicability in the Australian house building industry. The following table compares the results.

Table 5-20: The r-square for different predictions using Little's law

Lag	Original number of house completions	Number of house completions moving average
two quarters	76.6%	94%
three quarters	69.6%	84%

As demonstrated in the table, the best prediction is made by the moving average for number of house completions and with using two quarters lag. This is consistent with the result of error metrics. The r-square equals 94% shows a very high fit between predicted and actual data. This is further evidence for the applicability of Little's law in this case.

$NHUC_{pred}$ and $NHUC_{act}$ comparison using visual comparison: To see the conformity of the predicted and the actual NHUC, the two graphs are drawn on Figure 5-10. This figure shows that the predicted data follow the same trend as the actual data. The prediction is accomplished with very small error, demonstrating its predictive strength.

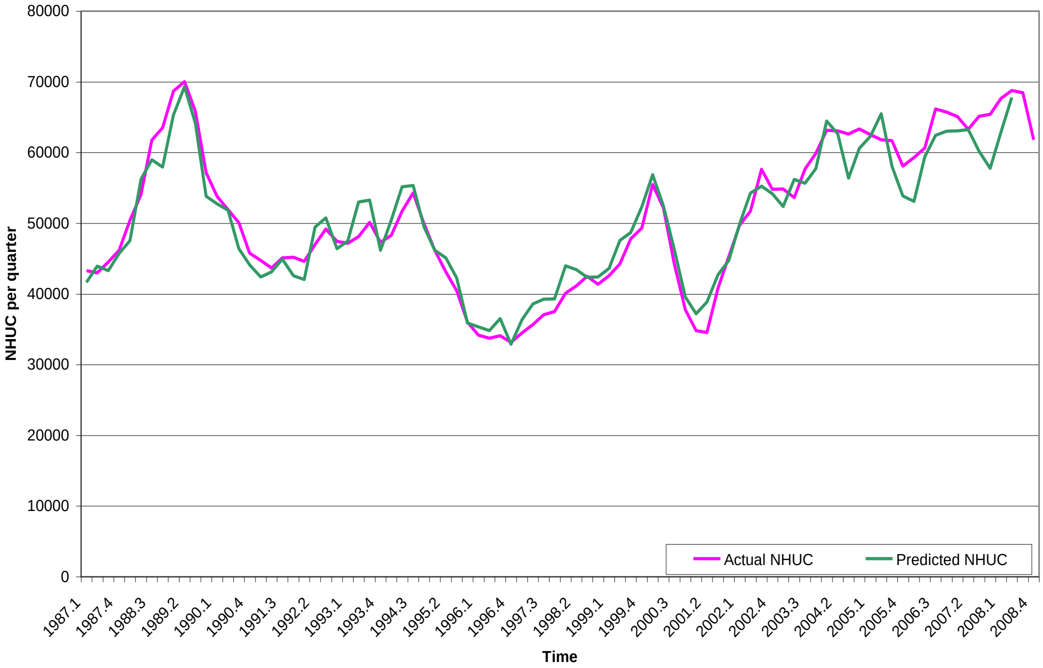


Figure 5-10: The comparison between predicted NHUC and actual NHUC in Australia

Applicability of Little's law in the Australian house building industry: The analysis done in this section shows the applicability of Little's law in the last case study at the national level. The r-square reported between the predicted and actual data was 94%, indicating a strong relationship between the predicted and actual data. The best prediction had an error of 4.24%, which is very low, and the visual comparison strengthened the proposition that Little's law is applicable in this state.

It was shown that the prediction should be made with two quarters lag, and moving average of number of houses under construction should be used rather than original data. Little's law for Australia is therefore, as follows:

$$NHUC_{(t)} = AHCT_{(t+2)} * NHC_{(t+2)} \qquad \textit{Equation 5-15}$$

Section summary

This part of the research aimed to verify the applicability of Little's law in the Australian house building industry. For this purpose, the work in process (WIP), cycle time (CT) and throughput (TH) in Little's law was replaced by the number of houses under construction (NHUC), average house completion time (AHCT) and number of house completions (NHC). Then the NHUC was calculated using the law and compared with the actual data obtained from the ABS reports.

The comparison was made using the error metrics and r-square between the predicted and actual NHUC as well as visual comparisons. The following table (5-21) summarises the result of the error metrics and r-square analysis. Note that the error metrics reported in this table is the mean absolute percentage error (MAPE) which does not have a scale and is a measure for the accuracy of a prediction.

As indicated in this table, the errors between the result of Little's law and actual data are very small. Most of r-squares are over 85%, which is an acceptable r-square for a prediction. The only States that Little's law returns more than 10 percent error are Queensland and NSW. This error was also explained using Little's law. It was shown that there is a house building capacity flowing from Queensland to the northern part of NSW. This makes an underestimation NHUC in NSW and overestimation of NHUC in Qld and, therefore, the errors in these two cases are higher than the other cases.

Table 5-21: The summary of MAPE and r-square for all cases

Case	MAPE	R-square
Australia	4.24%	94%
Victoria	5.23%	93.7%
Western Australia	7.84%	96.7%
South Australia	6.9%	93.8%
New South Wales	10.77%	83%
Queensland	16.56%	86.7%

The other method of comparison, which was used in this research, was visual comparisons. Figure 5-11 summarises the result of this analysis. As illustrated in this figure, the result of Little's law is very close to the actual data. This closeness is further evidence for the applicability of Little's law in the house building industry.

The applicability of the law shows that the house building industry works like a production line. The same relationship that exists between work in process, cycle time and throughput in a production line exists in the house building industry between number of houses under construction, average house completion time, and number of house completions. This result is a platform for further analysis of the industry using the workflow-based planning approach. This further analysis is done in following section.

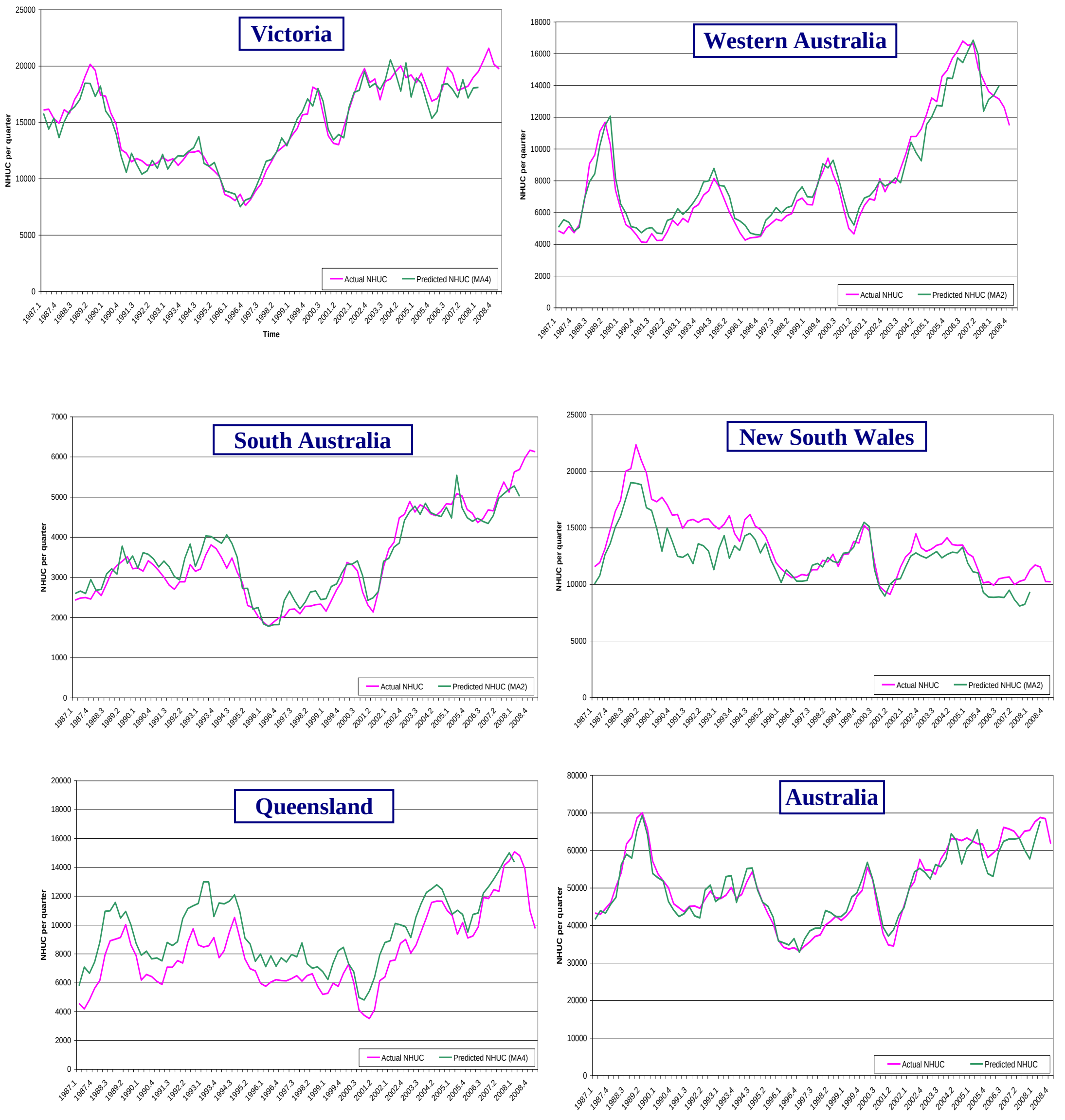


Figure 5-11: The comparison between the predicted and actual NHUC in all cases

5.3 *The relationships between number of houses under construction and completion time*

It was shown in Chapter four that the workflow-based planning approach can explain the reason for the changes in the trend of average house completion time by using the trend of number of houses under construction. The correlation between these two parameters was demonstrated by the graphs and time series for a twenty-year time span. However, the reason for this correlation was not explained.

The previous section showed that the parameter that relates average house completion time to the number of houses under construction is the number of house completions. Little's law, which has been shown applicable in the house building industry, explains this relationship. However, average house completion time is not only dependent on the number of houses under construction; it is also the result of the construction process and activity durations.

This section clarifies the relationship between the number of houses under construction and average house completion time. For this purpose, the relationship proposed by the workflow-based planning approach is explained and investigated in the house building industry. This investigation is undertaken in accordance with the research design using the multiple case study approach and replication logic. The five state cases and one national case that were studied in the previous section are also used in this part of the research.

Following sections include theoretical explanation of the NHUC-AHCT relationship and verification of the relationship in the house building industry.

5.3.1 NHUC-AHCT relationship

Previous sections showed that Little's law is applicable in the Australian house building industry. According to this law, the average house completion time is equal to number of houses under construction divided by number of house completions.

$$NHUC_t = AHCT_{t+l} * NHC_{t+l} \Rightarrow AHCT_{t+l} = \frac{NHUC_t}{NHC_{t+l}} \qquad \textit{Equation 5-16}$$

However, there is a minimum completion time for the construction of a house. This minimum time is not affected by number of houses under construction. For example, if construction of a house takes at least 6 months, even if there is only one house under construction, it is going to take six months to be constructed. This fact was explained in Chapter two (Section 2.3.2) describing the relationship between WIP and CT in a production system.

In the case of the house building industry, WIP, CT and TH can be replaced by number of houses under construction (NHUC), average house completion time (AHCT), and number of house completions (NHC). Therefore, Equation 2-2 becomes:

$$AHCT = \begin{cases} AHCT_0 & \text{If} \quad NHUC < NHUC_0 \\ \dfrac{NHUC}{NHC} & \text{Otherwise} \end{cases}$$

Equation 5-17

In this equation, the $NHUC_0$ is the critical number of houses under construction in which the average house completion time is at the minimum level. $AHCT_0$ stands for the minimum completion time and NHC is the number of house completions. Figure 5-12 is the visual interpretation of this equation, which is similar to figure 2-1.

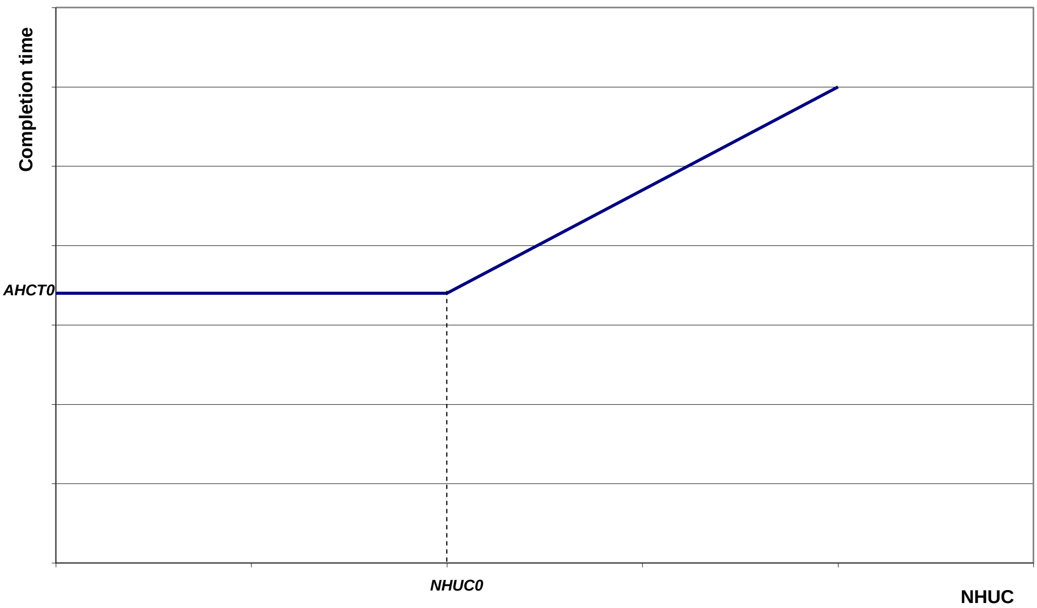


Figure 5-12: The hypothetical relationship between NHUC and AHCT

Although the relationship between work in process and cycle time is a principle in production planning, its translation to the house building industry (Equation 5-17) is a hypothesis. Following the verification of Little's law applicability in the house building industry, this part of the research investigate this new hypothesis on the relationship between NHUC and AHCT.

5.3.2 The NHUC-AHCT relationship in the Australian house building industry

Since the actual data for NHUC and AHCT is available, the investigation of this relationship is undertaken by drawing these two time series against each other. Every point in this graph has a dimension of (NHUC, AHCT). It was shown in the previous section that there is a lag between the NHUC and its related AHCT. This lag in Little's law is represented by *l* and has been found in case studies by the best predictions. Therefore, *l* for each case study is available and each point in the NUHC-AHCT graph has a $(NHUC_t, AHCT_{t+l})$ dimension.

Victoria

In this state, the lag proposed in Little's law is three quarters (Section 5.2.3). Therefore, the NHUC-AHCT graph is drawn by $(NHUC_t, AHCT_{t+3})$ points. The following figure illustrates this graph.

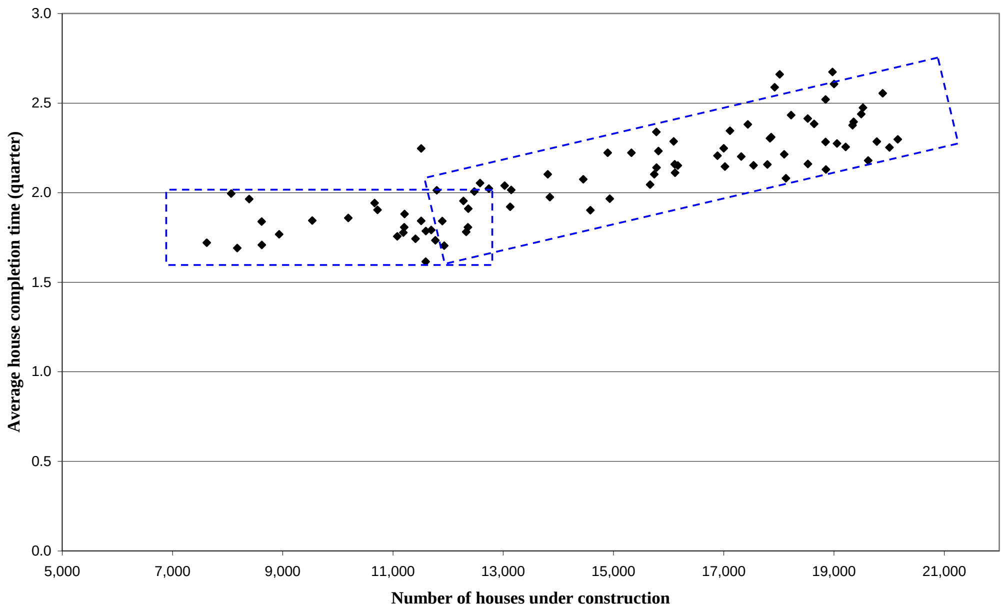


Figure 5-13: NHUC-AHCT relationship in Victoria

Figure 5-13 demonstrates that in this State, although the relationship between number of houses under construction and average house completion time is not as accurate as a straight line, it generally follows the NHUC-AHCT illustrated in Figure 5-12. This figure shows that for a wide range of NHUC, average house completion time stays between 1.6 and two quarters, while for the NHUC over this range, AHCT grows.

Western Australia

The analysis on NHUC-AHCT relationship in Western Australia is undertaken similarly to Victoria. The lag as it was concluded in Section 5.2.3 is two quarters for this state. Therefore, the NHUC-AHCT graph is drawn by the points with the dimensions of $(NHUC_t, AHCT_{t+2})$.

The growth of the AHCT by the increase of NHUC can be clearly seen in this case. Figure 5-14 demonstrates that average house completion time stays under two quarters for a wide range of NHUC and grows for the NHUCs above this range.

Western Australia is the second case that shows the validity of the suggestion by the workflow-based planning approach about the NHUC-AHCT relationship.

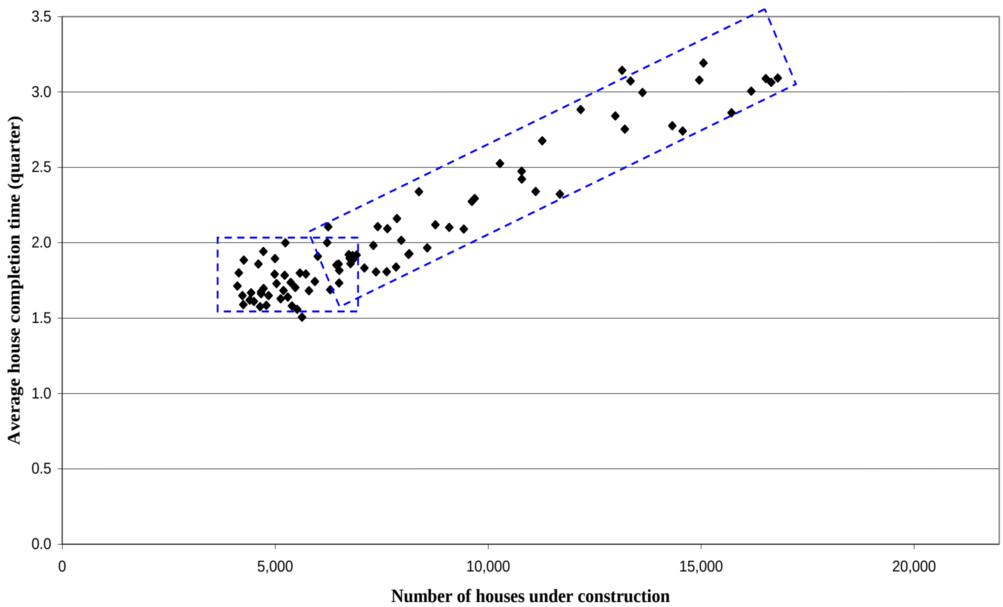


Figure 5-14: NHUC-AHCT relationship in Western Australia

South Australia

The previous two cases showed a production-like relationship between number of houses under construction and the average house completion time. In the case of South Australia, the lag between NHUC and its effect on AHCT is two quarters. This lag was found in Little's law analysis on this state in Section 5.2.3. Therefore, the NHUC-AHCT points in the following graph have $(NHUC_t, AHCT_{t+2})$ dimension.

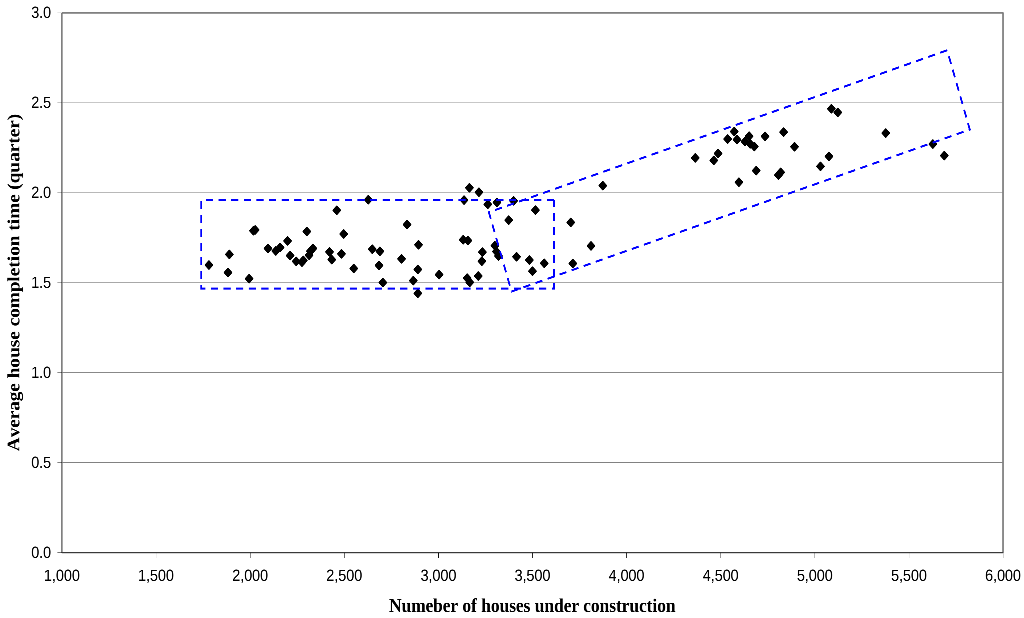


Figure 5-15: NHUC-AHCT relationship in South Australia

A pattern similar to previous cases is seen in South Australia. In this state, the average house completion times are between 1.5 to two quarters for a wide range of NHUC, and the increase of NHUC over this range leads to longer completion times.

New South Wales

New South Wales is the fourth case study in this part of the research. It was shown in Chapter four that while other states saw an increase in the number of houses under construction, NSW was the only state that faced a decline.

According to Little's law analysis in NSW, the lag between NHUC and AHCT is three quarters (Section 5.2.3); therefore, the dimensions were $(NHUC_t, AHCT_{t+3})$.

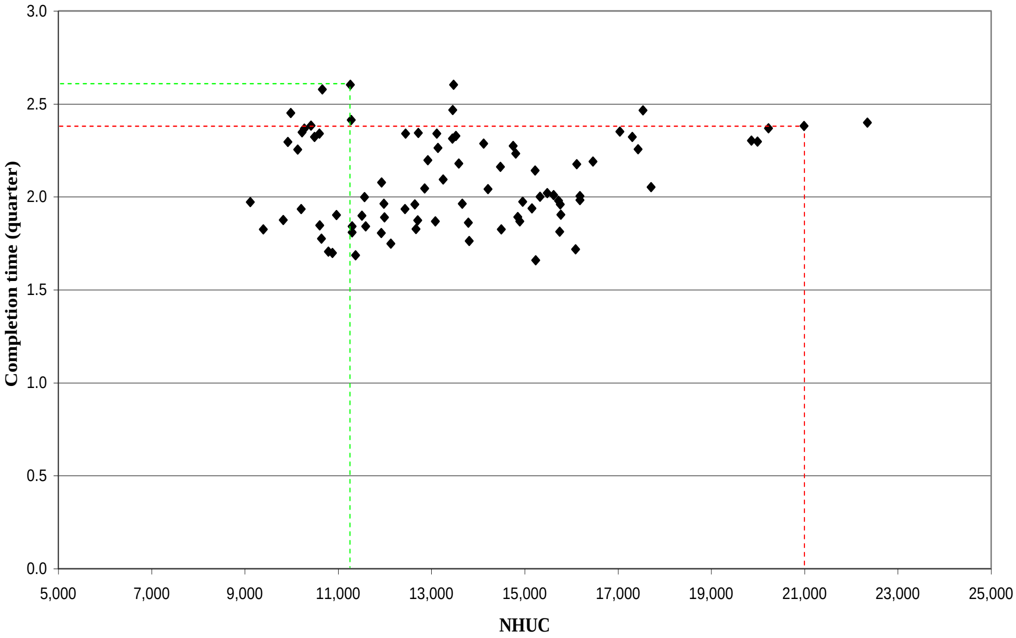


Figure 5-16: NHUC-AHCT relationship in New South Wales

As demonstrated in Figure 5-16, there is no pattern in the relationship between NHUC and AHCT for NSW. This figure shows that for different number of houses under construction the average house completion time can be between 1.5 to 2.5 quarters. Even for the NHUC level of 21,000 houses, the average house completion time is equal to or less than the average house completion time for the NHUC which equals 11,200.

This phenomenon is consistent with the fact that the house building industry in this state works in different circumstances to other states. These differences, and the reasons for the different NHUC-AHCT relationship in this state, are explained in the next chapter.

Queensland

Two quarters lag is proposed by Little's law for this state. It remains is to draw the points with the dimension of $(NHUC_t, AHCT_{t+2})$ in a graph and investigate the relationship proposed by the workflow-based planning approach.

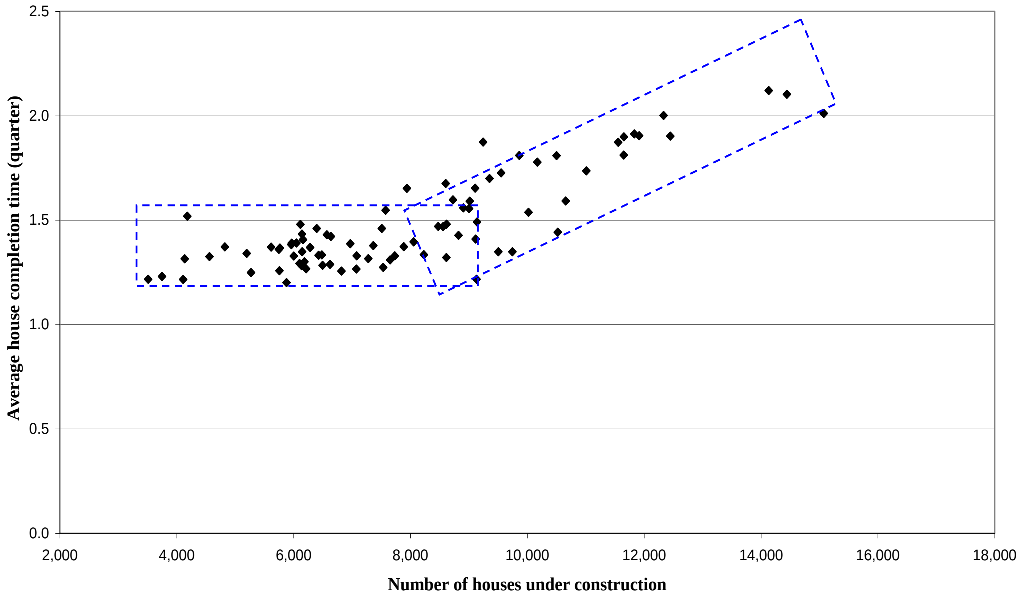


Figure 5-17: NHUC-AHCT relationship in Queensland

Queensland also shows the same kind of relationship between NHUC and AHCT. This relationship suggests that the house building industry in this state works like a production line. In this production line, as long as the number of houses under construction is under around 8,000 houses, the average house completion time is under 1.5 quarters. But when the NHUC exceeds this level, the average house completion time starts to increase.

Queensland is the fourth case that shows the validity of the NHUC-AHCT relationship suggested by the workflow-based planning approach. The next case is the national case of Australia.

Australia

Average house completion time and number of houses under construction are drawn in Figure 5-14. The lag is two quarters; therefore, each point in the following figure has the dimension of $(NHUC_t, AHCT_{t+2})$. This lag is suggested by Little's law analysis in Section 5.2.3.

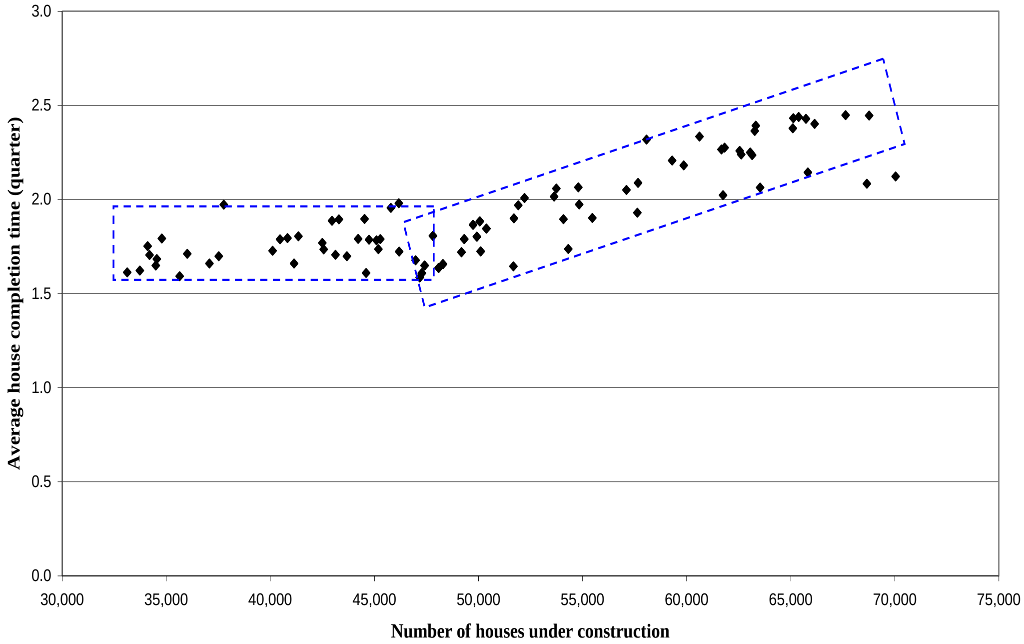


Figure 5-18: NHUC-AHCT relationship in Australia

As can be seen in this figure, a similar relationship to Figure 5-12 exists between NHUC and AHCT in the Australian house building industry. Although the data points are not precisely on a line, the overall trend of this relationship can be recognized. According to this figure, when the number of houses under construction is less than approximately 48,000 houses, the average house completion time tends to be between 1.6 and two quarters. As soon as the number of houses under construction grows above this level the average house completion time also grows.

Section summary

This section was dedicated to the verification of the NHUC-AHCT relationship proposed by the workflow-based planning approach. This approach suggests that average house completion time remains at a minimum level as long as the number of houses under construction is under its critical level. The AHCT grows relatively to the growth of the NHUC for the NHUCs over this critical level.

Six cases were investigated. These cases included five states of Australia, and the whole country as a national case. The results of the analysis of these cases showed that the relationship proposed by the workflow-based planning approach is valid in the Australian house building industry. The illustration of the theoretical relationship is shown in Figure 5-12 and its validations in Figures 5-13 to 5-18. A summary of the results for all six cases is shown in Figure 5-19.

Figure 5-19 shows that all of the cases follow a similar predicted trend, except NSW. The different behaviour in NSW is the outcome of a different situation for the house building industry in this state. The detailed explanation of this phenomenon in the NSW is presented in the next chapter.

This part of the research demonstrated that another aspect of the workflow-based planning approach, the relationship between WIP and cycle time, is valid in the house building industry. This relationship was referred as NHUC-AHCT in this research and proven with case studies and the use of actual data.

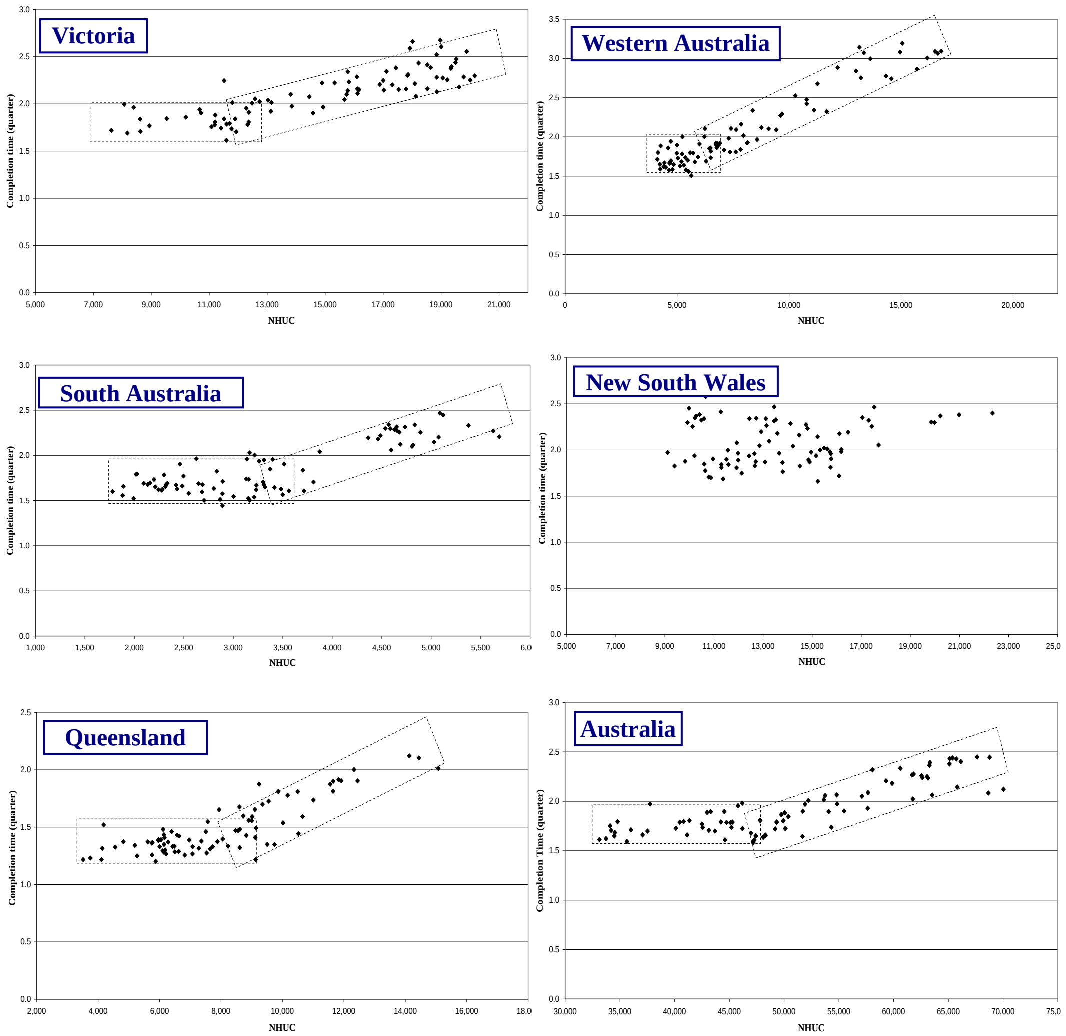


Figure 5-19: NHUC-AHCT relationship in all cases

5.4 Chapter Summary

This chapter addressed the second objective of the research and focused on the verification of Little’s law applicability and NHUC-AHCT relationship in the house building industry. Both of these concepts are related to house completion time and are based on the workflow-based planning approach.

The verification of these concepts was achieved through six case studies. This chapter showed that the same kind of relationship that exists between work in process, cycle time and throughput, exists in the house building industry between average house completion time, number of houses under construction and number of house completions. Since this law is designed for a manufacturing process, it was modified to suit house building industry. The modification included the amendment of time factor to the law.

Further, workflow-based planning proposes a special pattern for the relationship between NHUC and AHCT. This pattern was also examined in this chapter and was proved valid for the house building industry. According to this pattern, the AHCT stays at its minimum level when the NHUC is under the critical level. The growth of NHUC over the critical level causes the AHCT to relatively extend.

The verification of Little’s law and validity of the NHUC-AHCT relationship in the house building industry leads to the conclusion that the workflow-based planning approach can predict and explain the behaviour of the house building industry. This conclusion opens a new perspective to the industry and can lead to better understanding of its behaviour. The next chapter follows this conclusion and uses this planning approach to further analyse the Australian house building industry.

6 CHAPTER SIX - AVERAGE HOUSE COMPLETION TIME; THE INDICATOR OF HOUSE BUILDING INDUSTRY CAPACITY

6.1 Introduction

Previous chapters demonstrated that there is a correlation between average house completion time and number of houses under construction in Australia. This correlation was further investigated using Little's law and the relationship was explained between average house completion time, number of houses under construction, and number of house completions. This correlation and relationship were the first two objectives of the research described in Chapter three.

Now that the applicability and validity of the workflow-based planning approach in the Australian house building industry is demonstrated, this chapter focuses on the third objective of the research and explores the implications of this approach in understanding the industry's behaviour. In this regard, this chapter examines the fundamental concept of the critical number of houses under construction and the industry's capacity. This examination is followed by an estimation of the critical level for each State and the whole country. Then it continues with the current situation of the industry and explains the industry's dynamics using the workflow-based planning approach.

The next section starts this exploration with investigation of the critical level of number of houses under construction.

6.2 Critical number of houses under construction $(NHUC_0)$

In the previous chapter, the relationships were explained between work in process and cycle time, or in housing terms, between number of houses under construction (NHUC) and average house completion time (AHCT). This explanation included a graph (Figure 5-12) that showed the AHCT for the different levels of NHUC. This graph has been reproduced below in Figure 6-1.

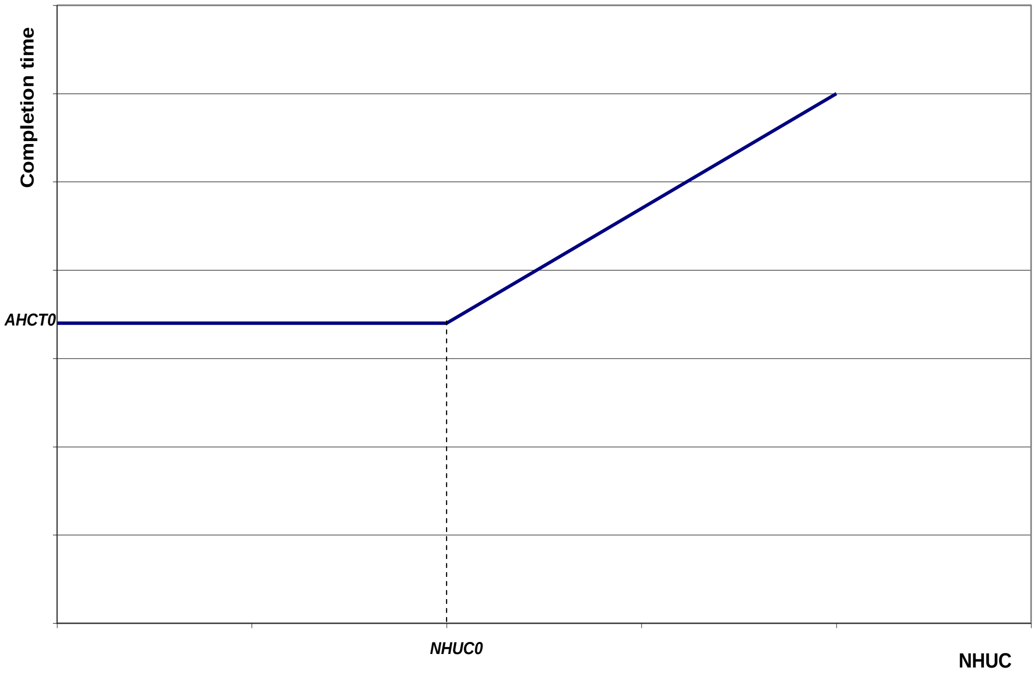


Figure 6-1: The theoretical NHUC-AHCT relationship

Figure 6-1 shows that average house completion time remains at a minimum level for the NHUCs under the $NHUC_0$ level. Therefore, the critical NHUC $(NHUC_0)$ is the maximum number of houses under construction that the industry can work on without affecting the completion time.

The extension of the completion time over the minimum level signals a waste in time. This extra time is the idle time in the construction process. This is the time that there are insufficient resources in the industry to work on the houses. Thus, it can be said that the critical NHUC is the maximum level of work load that minimise waste of time in the process of construction.

This maximum level of workload is called industry's capacity in this research. Knowing the capacity helps policy makers and entities involved in the industry to understand the industry better and make decisions that are more effective.

The NHUC-AHCT relationship explained above is the theoretical relationship in a steady system. However, the house building industry is a dynamic system which is always changing and responding to external factors. Therefore, as was shown in the previous chapter, the linear deterministic relationship between NHUC and AHCT in fact becomes a stochastic relationship in the house building industry. This stochastic relationship follows the same trend as the deterministic one. In this trend, instead of an exact average house completion time for a specific number of houses under construction, the completion time falls between a range of times.

To clarify this phenomenon a hypothetical relationship between NHUC and AHCT in a house building industry is demonstrated in the following figure (6-2). This hypothetical graph is an example similar to the actual graphs illustrated in the previous chapter for the Australian house building industry.

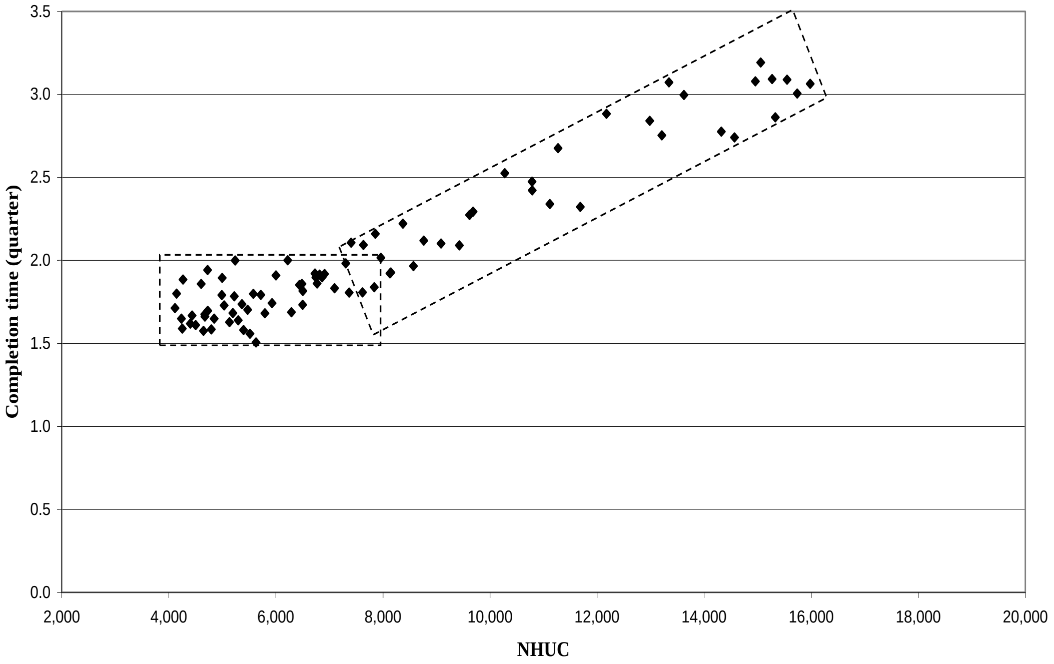


Figure 6-2: NHUC-AHCT relationship for a hypothetical house building industry

For example, in Figure 6-2, there is a range of completion times for the number of houses under construction under 8,000. This range is shown by a rectangular box in the figure. This range is confined between 1.5 and 2 quarters and does not exceed this limit.

Considering the stochastic behaviour of the industry, it can be seen in Figure 6-2 that the industry still follows the trend of the theoretical relationship between NHUC and AHCT. This similar trend was explained in the previous chapter in the Australian house building industry.

6.3 Finding the critical NHUC and industry analysis

The critical NHUC is a turning point in the behaviour of the house building industry. This is the point at which the industry reaches its capacity and cannot efficiently work on more jobs. Extra jobs have to wait and consequently their completion time increases. With this explanation, the turning point in an industry points to both its critical NHUC and its capacity.

This part of the research attempts to find the critical NHUC in the Australian house building industry. For this purpose, the NHUC-AHCT graphs are drawn and the turning points are calculated. This analysis is undertaken using linear regression for two different phases of the relationship. The first phase is the range of NHUCs, which give constant AHCT, and the second phase is the range of the NHUC, which has a direct relationship with AHCT.

Then the critical NHUC and minimum AHCT are used in the explanation of industry's behaviour during the study period. This explanation is based on the workflow-based planning approach and emphasizes the use of average house completion time as an indicator of the industry's capacity and its state of supply.

Following sections investigate this aspect on the case studies used in the previous chapters and explain the house building industry's behaviour in five States and the whole country. Similar to chapter four and five, Victoria is the first State in this investigation. This State is used as a pilot case for the study and the analyses are explained in detail for this case. The next cases follow the same kind of analysis.

6.3.1 Victoria

Chapter five showed that the house building industry in Victoria works like a production line. In this industry the relationship between number of houses under construction and average house completion time is similar to the relationship between work in process and cycle time in a production line. Following figure demonstrates this relationship.

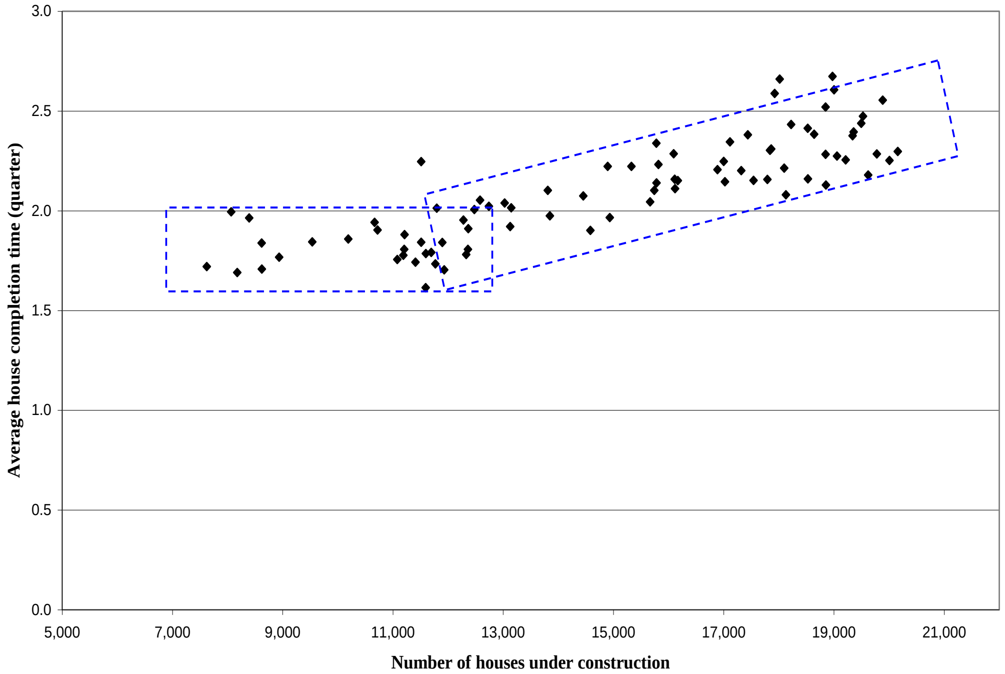


Figure 6-3: NHUC-AHCT relationship in Victoria

There are two phases in the NHUC-AHCT relationship which are schematically demonstrated by rectangular boxes in Figure 6-3. The first phase is the range of NHUC in which the completion time keeps in a constant range, and the second phase in which the AHCT increases by the increase of NHUC.

To show these two phases more precisely, regression analysis has been used. As there are two phases in this relationship, a separate regression has been made for each of them. However, as the data intersecting the two phases cannot confidently be assigned to either phase, they are eliminated from the analysis. Figure 6-4 shows this elimination and the result of the linear regression.

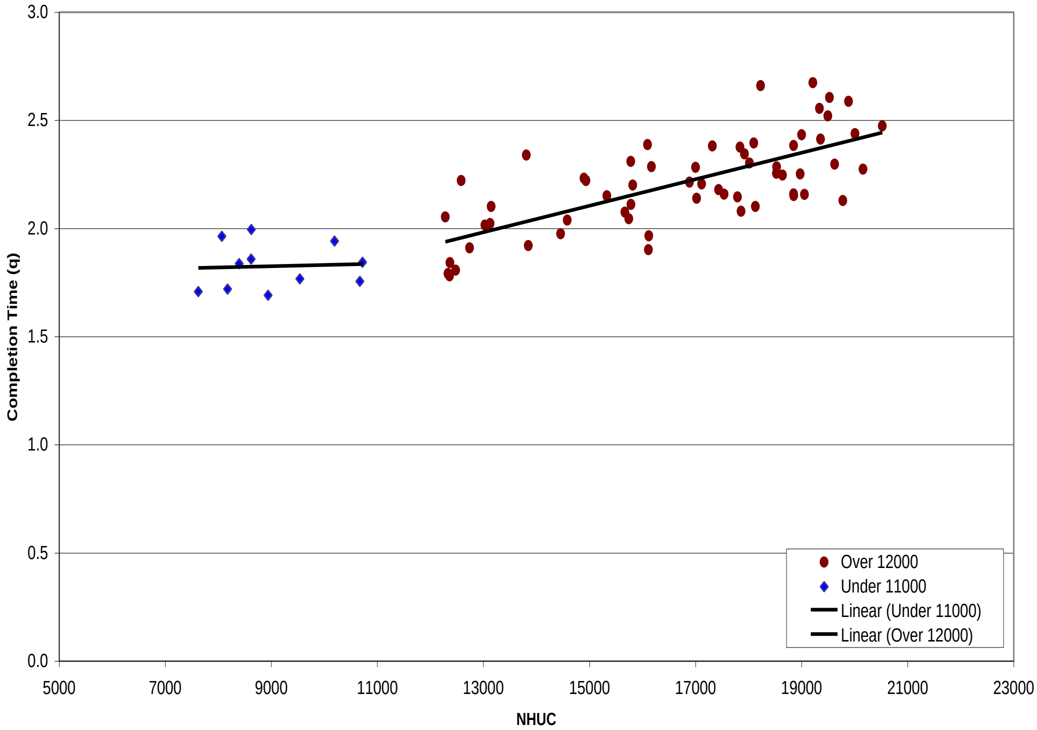


Figure 6-4: The regression analysis on the NHUC-AHCT relationship in Victoria

In this figure, the blue data points demonstrate the range of NHUC in which the average house completion time remains around 1.8 quarters. The red points show the situation in which the number of houses under construction increases with a corresponding increase in average house completion time. As Figure 6-4 shows, the NHUC data points between 11,000 and 12,000 houses are omitted from the analysis. The two phases in the relationship can be clearly seen in this regression.

The critical NHUC is the turning point between the two phases. The intersection of the two trend lines determines this turning point. For this purpose the trend lines are extended and the intersection is found. Figure 6-5 shows the result.

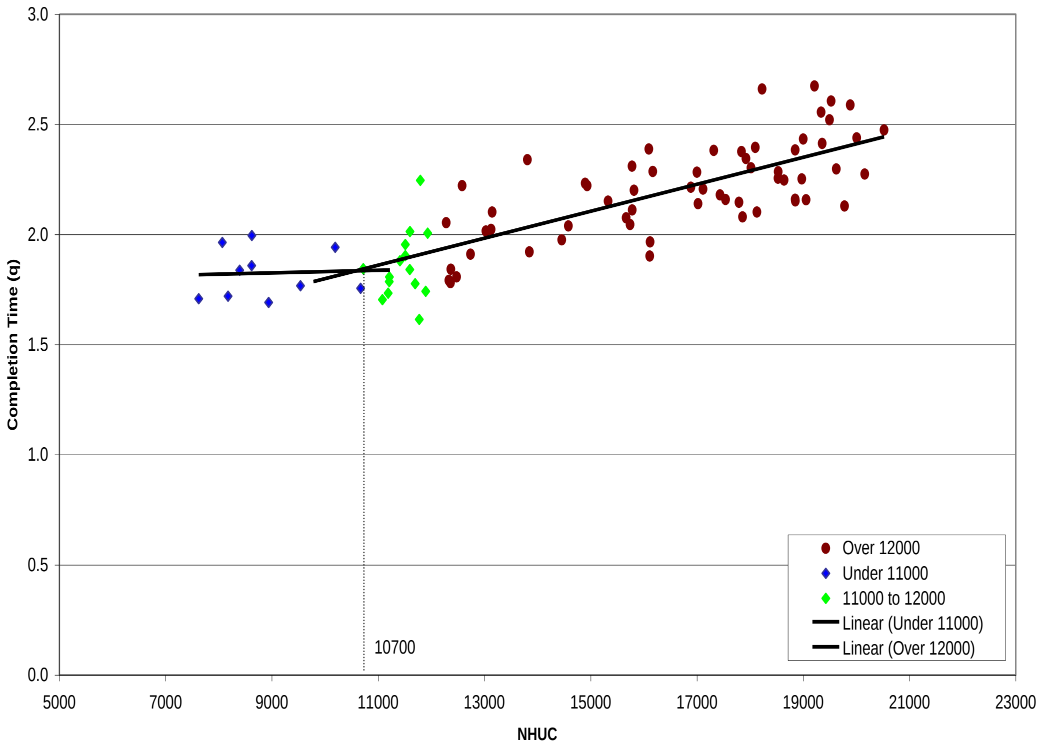


Figure 6-5: The critical NHUC in Victoria

As can be seen in this figure, the critical number of houses under construction for the Victorian house building industry is around 10,700 houses.

Note that this number roughly indicates the capacity of the house building industry. The house building industry apparently has its own flexibility that makes its behaviour stochastic. Finding out an absolute capacity of the industry can be misleading. However, this research shows that with all the flexibility and changes in the industry, the overall behaviour of the industry is similar to a production line with a limited capacity. This capacity for the house building industry in Victoria is around 10,700 houses.

Figure 6-5 shows that for a majority of the time, the house building industry in this state has worked over capacity. This phenomenon can be seen with the high number of data points in the second phase of the NHUC-AHCT relationship.

The other parameter in the relationship of the NHUC and AHCT is the minimum AHCT. This parameter for this case is calculated with the average of AHCT in the first phase. The result was 1.8 quarters. This minimum level of average house completion time is used later in this chapter for the explanation of the house building industry behaviour.

Industry analysis:

According to the workflow-based planning approach, if the actual NHUC goes over the $NHUC_0$ line, the AHCT is expected to go over its minimum level, and if the NHUC goes under the critical level the AHCT is expected to remain at its minimum level. Therefore, to verify and validate the estimated values of the critical NHUC and minimum AHCT in Victoria, these parameters are drawn in the same graph, with the actual trend of NHUC and AHCT, in Figure 6-6.

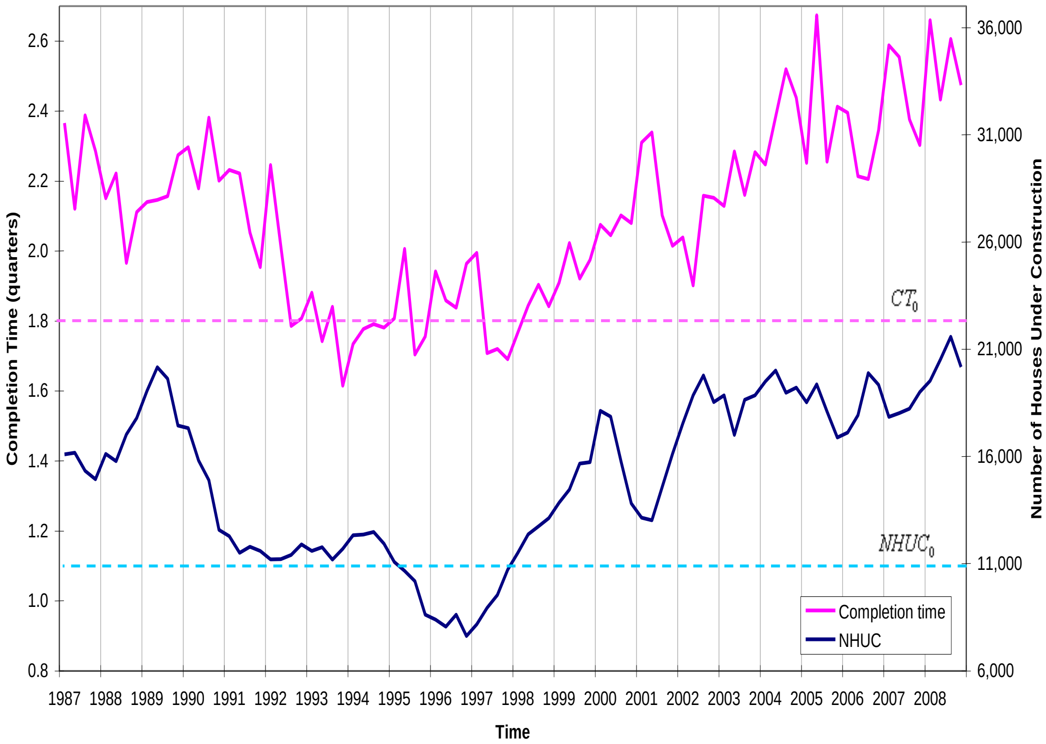


Figure 6-6: NHUC and AHCT trend in Victoria

As demonstrated in this figure, the NHUC is over the critical level from 1987 till mid-1991. Therefore, the workflow-based planning approach predicts the average house completion time to be longer than minimum level. Figure 6-6 shows that the prediction is valid and in this period the average house completion time is over the minimum level.

Mid-1991 to mid-1993 is the period in which the NHUC is at the critical level and, thus, the AHCT is expected to be around the minimum level. The AHCT trend shows that the average house completion time is around the minimum AHCT for this period. The peak point of NHUC in mid-1994 causes an increase in AHCT in the beginning of 1995.

The low level of NHUC during 1996 makes the AHCT decrease to its minimum level in 1997, and the increase of NHUC since 1998 makes the AHCT ascend over its minimum level. All these demonstrate the validity of the workflow-based planning explanation of changes in house completion time.

It was shown that whenever the average house completion time is longer than the minimum level indicated for the industry, there is a shortage in house building capacity and industry is over capacity. Consequently there is not sufficient number of houses built and there is a shortage of housing supply in the market. Therefore, the AHCT can be an indicator of industry's status in terms of capacity and supply.

In the case of Victoria, the AHCT over 1.8 quarters indicate this shortage. Noteworthy is the state of capacity in this State during last twenty years. This analysis shows that Victorian house building industry has seen a shortage of capacity, and therefore, a shortage of housing supply for the majority of time during this period.

6.3.2 Western Australia

The two phases of relationship between NHUC and AHCT for Western Australia were investigated in the previous chapter. These two were shown by the rectangular boxes in that chapter (Figure 5-16).

In this chapter, the main focus is on the turning point between these two phases. Thus, the rectangular boxes are replaced by the linear trend line for each phase. The intersection of these two trend lines indicates the turning point, and this turning point determines the critical number of houses under construction and the industry's capacity.

The two phases and their trend lines are drawn in Figure 6-6. In this figure, the number of houses under construction between 6,000 and 8,000 are eliminated from the analysis. This range of numbers is the transition area between two phases and its elimination clarifies the differences between two phases.

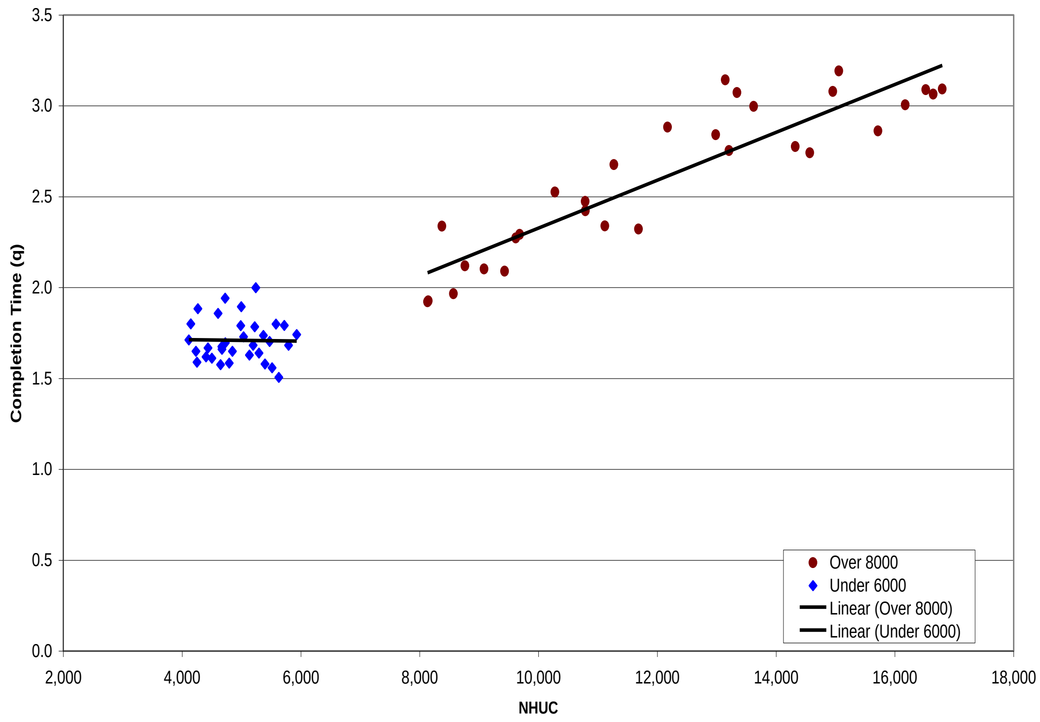


Figure 6-7: The trend lines for the two phases of the NHUC-AHCT relationship in Western Australia

Figure 6-7 illustrates that the completion time remains around 1.7 quarters in the first phase, and in the second phase, it increases as the NHUC grows.

To find the turning point between these two phases, the trend lines are extended and their intersection is calculated. Following figure (6-8) shows the result.

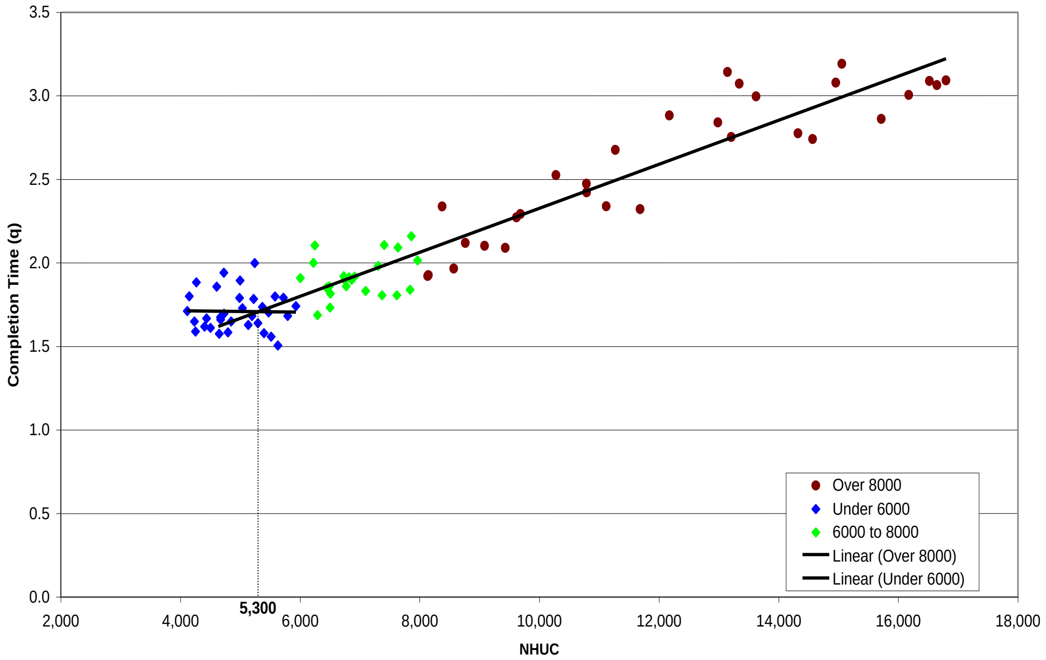


Figure 6-8: The critical NHUC in Western Australia

The data for the NHUC between 6,000 and 8,000 are added to the graph in Figure 6-8 to show that the trend lines also cover this area. According to this graph, the turning point is around 5,300 houses. This number is the critical number of house under construction which is the best level of work load for the house building industry in this state. The NHUCs over this level return longer completion times.

Industry analysis:

Historical trend of AHCT and NHUC are drawn in the same figure (6-9) to demonstrate the potential of these parameters for the analysis of the house building industry, and to show the application of AHCT as an indicator of house building capacity status.

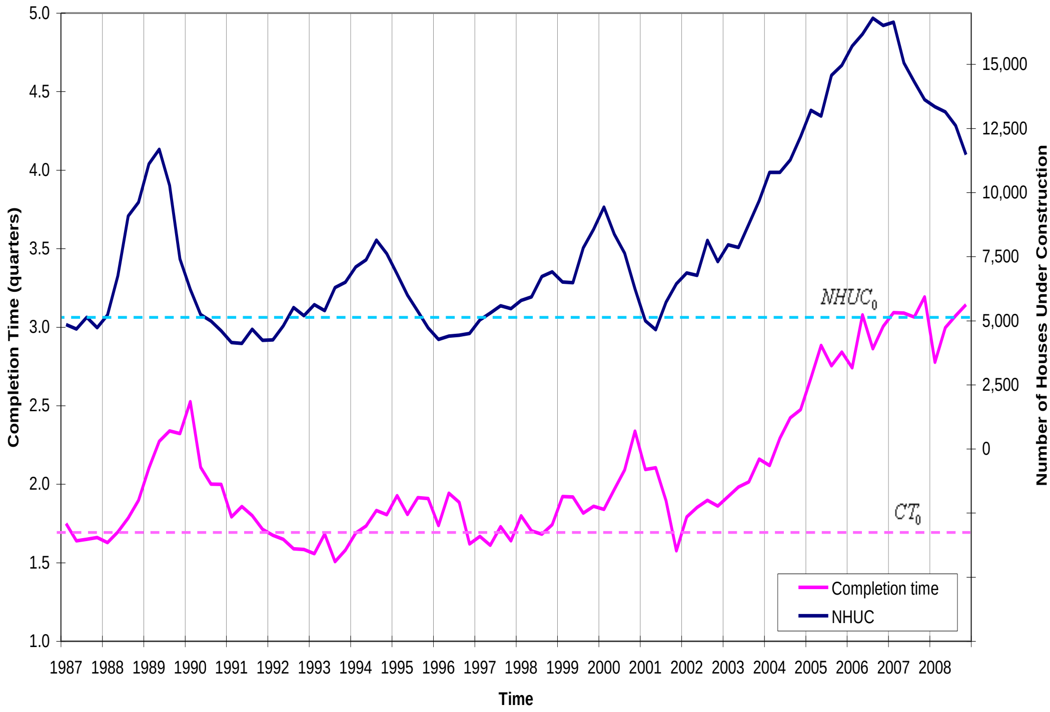


Figure 6-9: NHUC and AHCT trend in Western Australia

The dotted blue line in Figure 6-9 is the critical NHUC level and the dotted pink line is the minimum AHCT (1.7 quarters).

As can be seen in this figure the NHUC was around the critical level in 1987. Consequently, the completion time stayed at the minimum level. The year 1988 to mid-1990 faced a peak in the NHUC. This peak is expected to return a peak point in the AHCT. Figure 6-9 show, that the average house completion time reached a maximum at the beginning of 1990. According to the workflow-based planning approach and NHUC-AHCT relationship, the decline of NHUC to a level below the critical level is expected to minimize the AHCT. This can be seen by the AHCTs at the minimum level in 1991-1992.

Note that there is a lag between the changes in NHUC and their effect on AHCT. This lag was explained in Chapter five and was estimated and added to Little's law for this state.

Figure 6-9 illustrates the growth of NHUC over 5,300 houses between 1993 and 1996, which causes the completion time to grow beyond its minimum level. The NHUCs under 5,300 houses in 1996 helps the AHCT reach its minimum level and the NHUCs over this level in 1997-2001 causes the AHCT to peak at the end of 2001. The general trend for the NHUC since 2001 is increasing and this increase leads to an increase in the completion time in this period.

As was shown in Figure 6-9, the 5,300 houses estimated above is the turning point in the behaviour of the industry and its capacity. Further, the extension of house completion time over 1.7 quarters was associated with house building working over its capacity. The industry that works over capacity does not have sufficient resources to build more houses, and therefore, there would be a supply shortage in the housing market. Figure 6-9 shows that this state has seen this shortage in four periods of time during past twenty years.

6.3.3 South Australia

A similar method to the previous cases is implemented to find the critical NHUC for South Australia. The two phases of NHUC-AHCT relationships are separated. The trend lines for each of these phases are drawn and the intersection of the two trend lines is determined. Figure 6-10 shows the two phases and their trend lines.

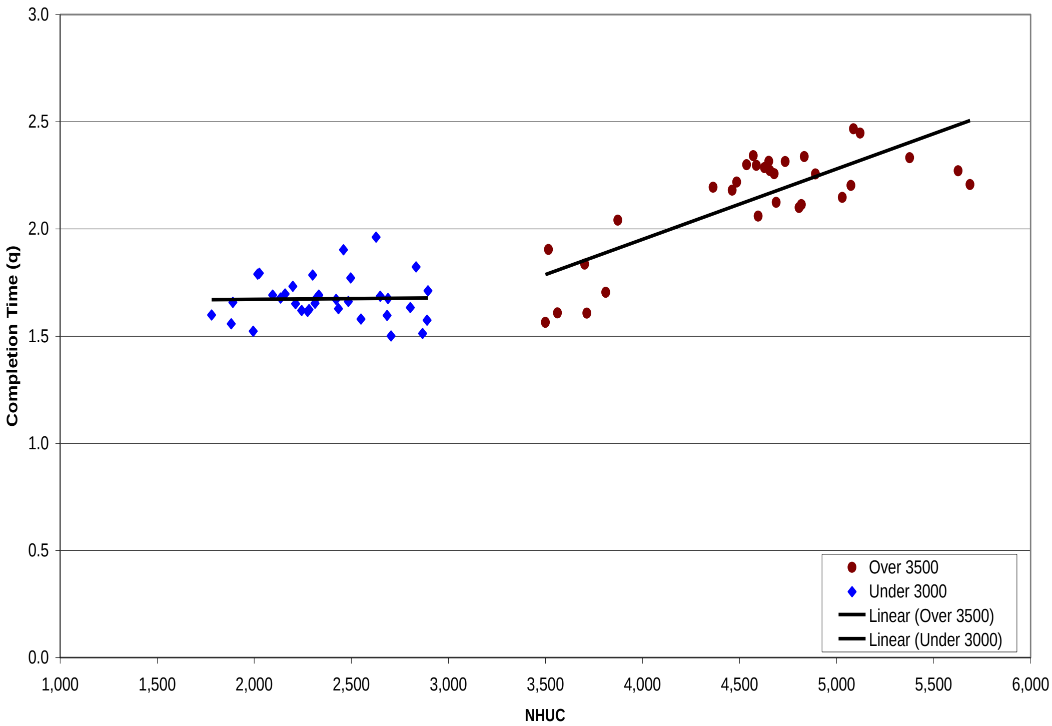


Figure 6-10: The trend lines for the two phases of the NHUC-AHCT relationship in South Australia

As can be seen in this figure, the transition area is eliminated from the graph. This is due to the fact that at this stage it is not known that the data in this part of the graph belongs to which phase. This transition data points are the NHUC between 3,000 and 3,500 houses.

Figure 6-10 clearly shows the two phases of the NHUC-AHCT relationship. The next step is to find the turning point between the phases which is considered as the critical number of houses under construction. Figure 6-11 illustrates this point.

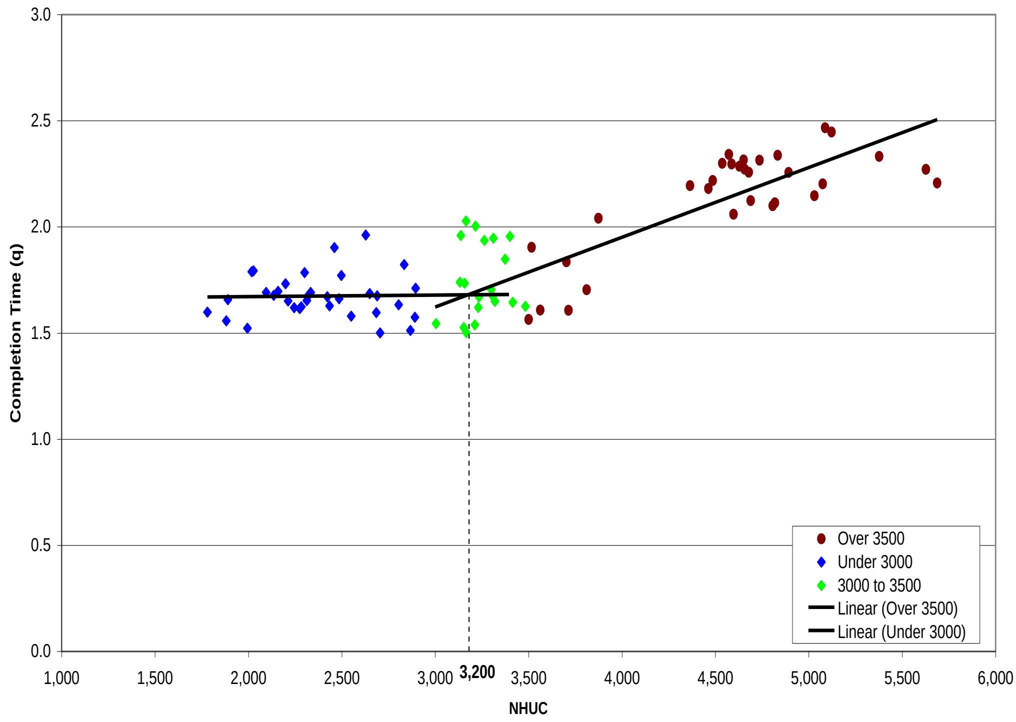


Figure 6-11: The critical NHUC in South Australia

The transition area is also added to the graph in Figure 6-9. The turning point occurs at NHUC around 3,200 houses. Thus, 3,200 houses is the estimated capacity for house building in this state. The AHCT of 1.7 quarters is also determined as the minimum AHCT in this state.

Industry analysis:

Knowing the critical NHUC and minimum AHCT, the workflow-based planning approach suggests that the South Australian house building industry is expected to face an increase in the average house completion time if it works on more than 3,200 houses. The average house completion time is expected to stay at the minimum level (1.7 quarters) when the industry works under this level. To investigate this behaviour, the trends of AHCT and NHUC are shown in the next figure (6-12).

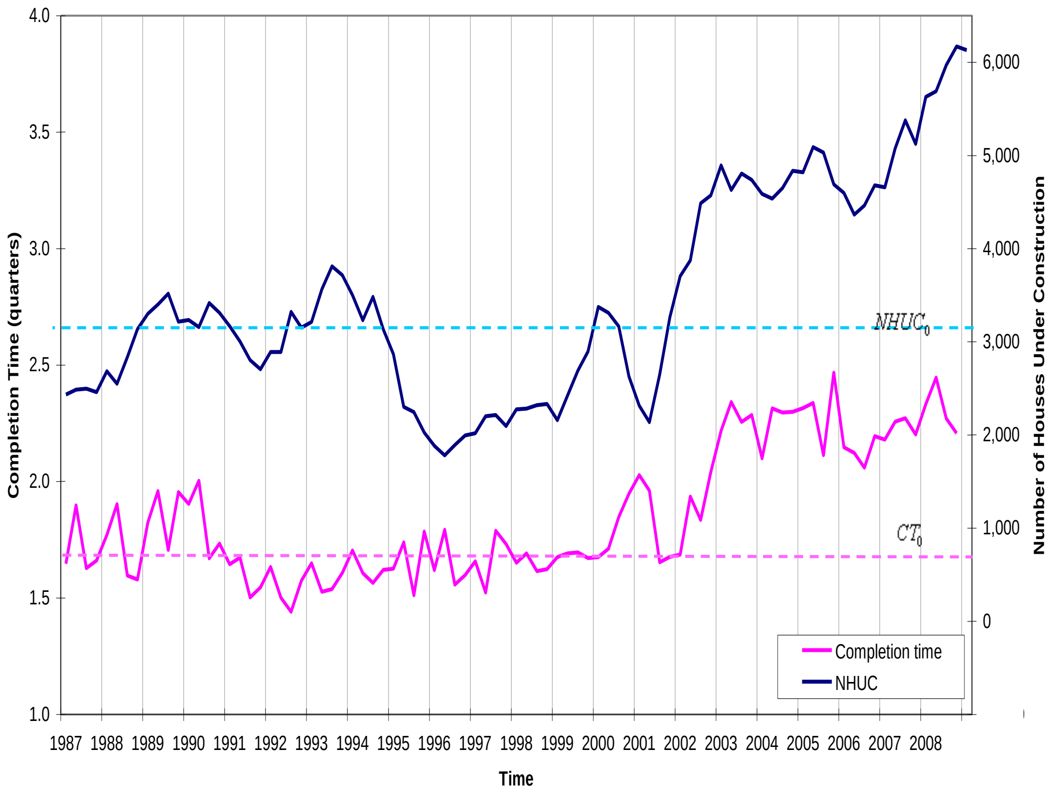


Figure 6-12: NHUC and AHCT trend in South Australia

Figure 6-19 shows that the number of houses under construction fluctuates from 1987 till the end of the 1990s. But this fluctuation is not followed by the average house completion time. This is due to the fact that in this period the industry is in its first phase and NHUC is around critical level or under it. Therefore, the changes in NHUC do not affect the AHCT, and thus AHCT remains around its minimum level.

The growth of NHUC over its critical level since 2002 makes the industry move to the second phase. In this phase, the changes in NHUC are reflected in the trend of AHCT. This phenomenon can be clearly seen in Figure 6-12.

According to this analysis, average house completion times longer than 1.7 quarters point to the lack of house building capacity in the industry, and therefore, the market suffers from a shortage of housing supply.

6.3.4 New South Wales

As explained in Chapter five (Section 5.3.2), New South Wales did not follow the same trend as the other States. This State did not show the two phases in the NHUC-AHCT relationship (Figure 5-16). However, it was mentioned that this phenomenon can also be explained by the workflow-based planning approach and NHUC-AHCT relationship. To explain this, the time factor is added to NHUC-AHCT graph and is shown in Figure 6-13.

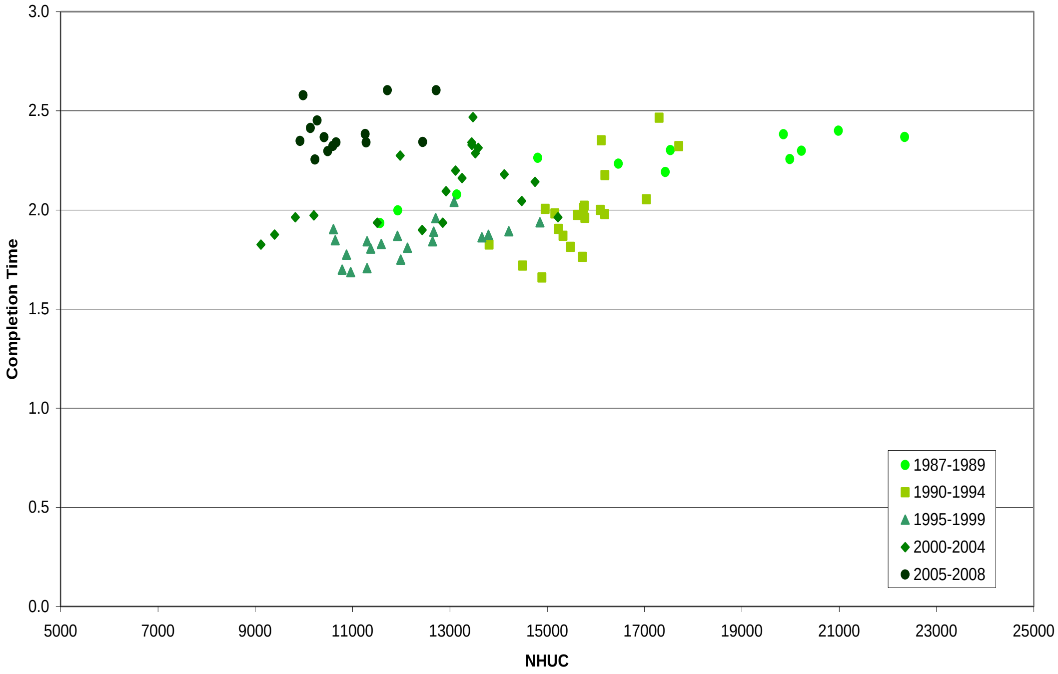


Figure 6-13: NHUC-AHCT relationship in New South Wales

Figure 6-13 shows that the house building industry flourished in this state in the late1980s. The NHUC in this period was around 21,000 houses. During the early 1990s the NHUC is around 16,000 and the declining trend continued until recent years.

This trend is also demonstrated in Figure 6-14. The declining trend of NHUC caused the capacity built in the late 1980s and early 1990s to appear not to have been saturated since then. The house building industry in this State, in contrast with other States, has continued to work under capacity.

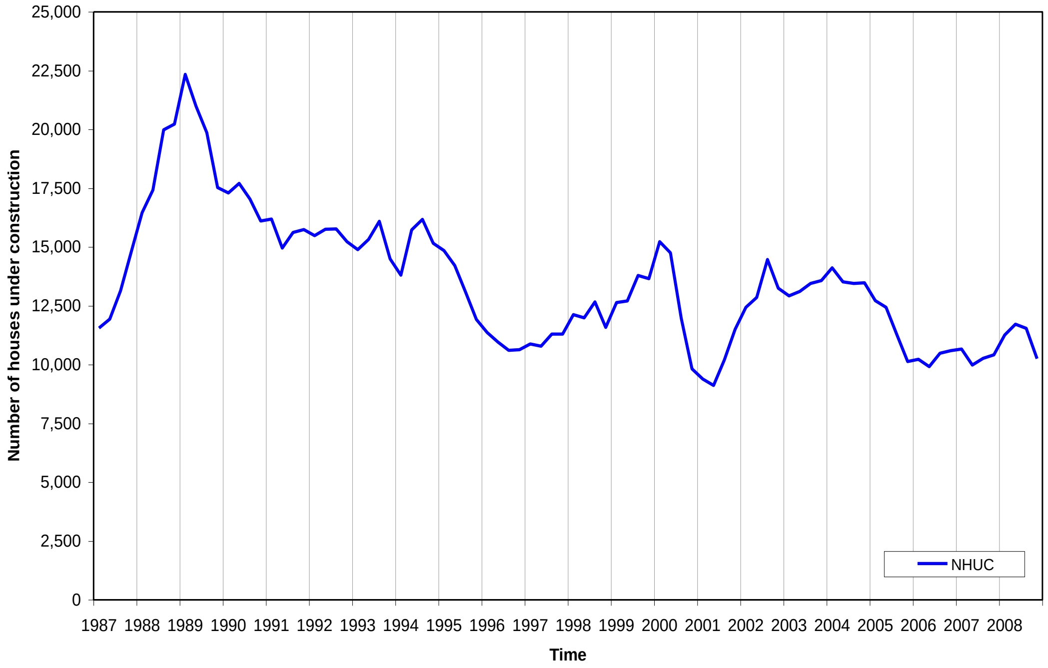


Figure 6-14: NHUC and AHCT trend in New South Wales

As described in the previous cases, whenever the industry is working under capacity, the NHUC-AHCT remains in its first phase. This phenomenon explains the NHUC-AHCT relationship seen in this State. In other words, the NHUC-AHCT in NSW is not similar to the other States because it reflects only one phase in which the industry continued to work under capacity. And since this state has not reached its capacity, the critical NHUC cannot be found.

6.3.5 Queensland

Queensland is the last case study at the State level. Similar to previous cases, the two phases of NHUC-AHCT relationship are separated in this case and the trend line for each phase is drawn. The transition range of NHUC in this case is between 7,500 to 8,500 houses. Thus, the data points for this range are removed. Following figure (6-15) shows the two phases of NHUC-AHCT relationship and their trend lines.

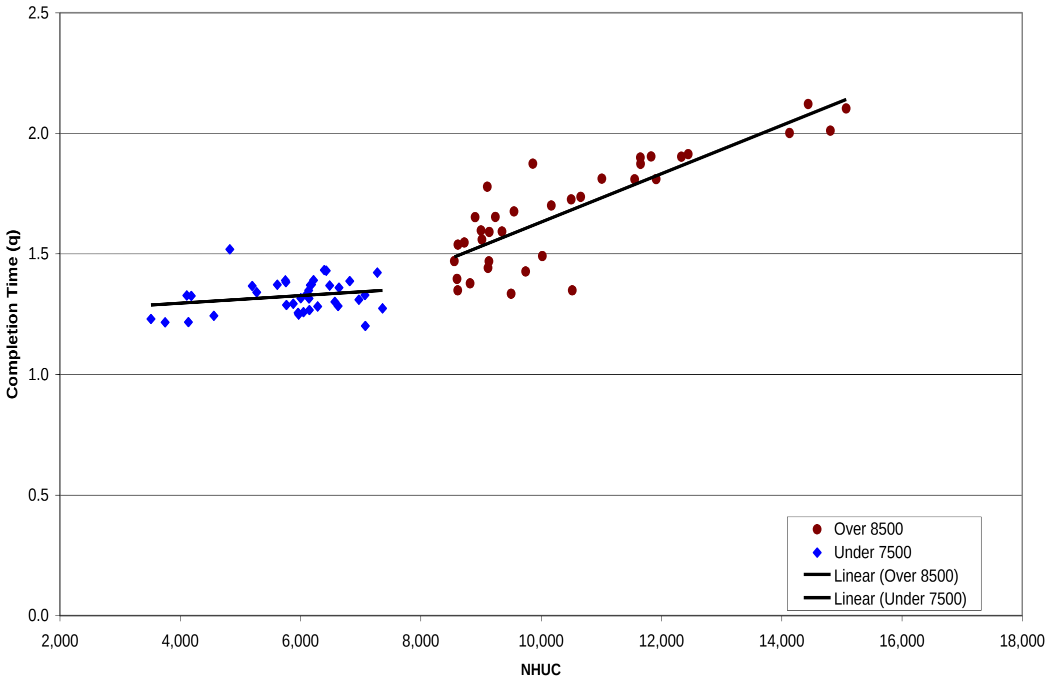


Figure 6-15: The trend lines for the two phases of the NHUC-AHCT relationship in Queensland

The trend lines in this graph are extended to cross each other. The intersection of these two lines shows the turning point which is the critical number of houses under construction.

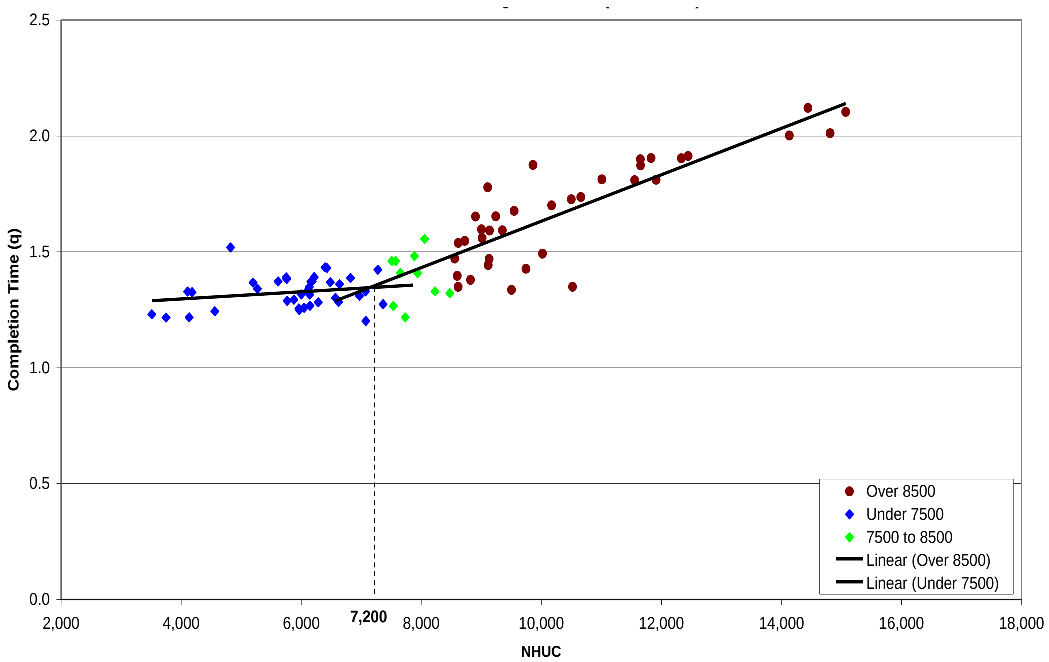


Figure 6-16: The critical NHUC in Queensland

As demonstrated in Figure 6-16, the two trend lines intersect at around 7,200 houses. Therefore, this point is considered as the critical number of houses under construction. The minimum average house completion time for this state is 1.3 quarters. This duration is the completion time that can be achieved by NHUC under 7,200 houses.

Industry analysis:

The estimated critical NHUC and average minimum completion time are 7,200 houses and 1.3 quarters in Queensland. To show the strength of the workflow-based planning approach in explanation of Queensland house building industry's behaviour, the NHUC and AHCT trends are drawn in the same graph and the critical NHUC and minimum AHCT are indicated. The following figure shows the result.

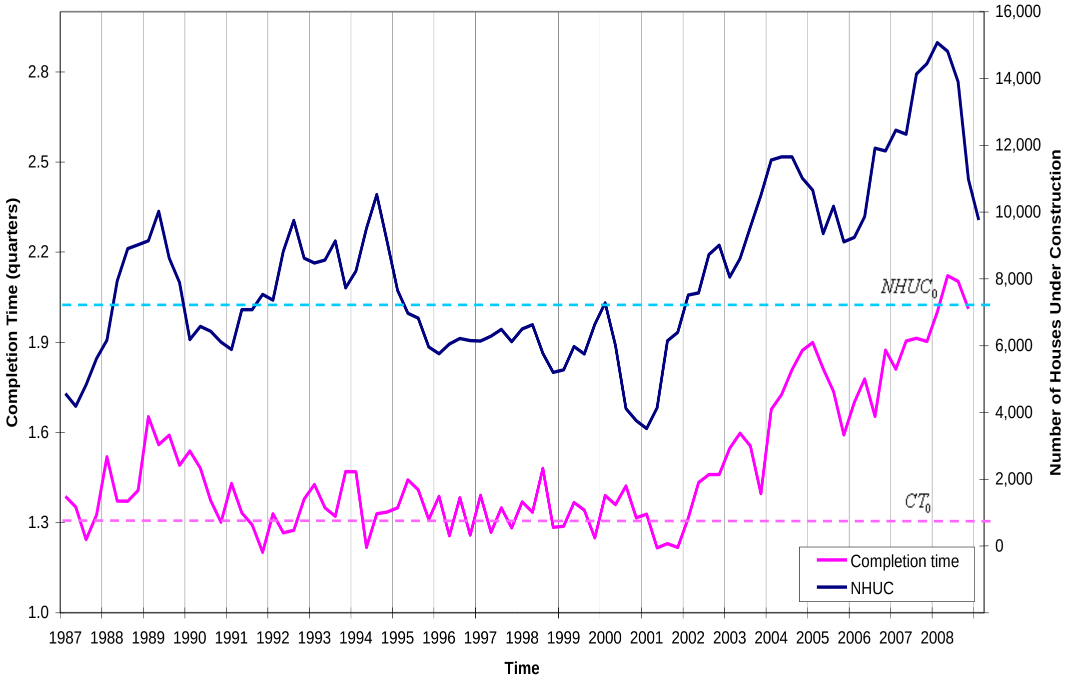


Figure 6-17: NHUC and AHCT trend in Queensland

As the workflow-based planning approach suggests, NHUCs over critical level in 1988-1990 cause the AHCT to grow over its minimum level. This peak point is followed by a drop in the NHUC in 1991 when it goes under the critical level. The same drop can be seen in AHCT at the end of this year. However, AHCT drops only to its minimum level. The following years, between 1992 and 1995, show the growth of NHUC over its critical level and the AHCT over the minimum level.

The seven years after this period faced a decrease in the number of houses under construction. This decrease returned the industry to its first phase where the changes in NHUC do not affect the AHCT. In this period, the AHCT remains at its minimum level and does not follow the ups and downs in NHUC. For instance, the dramatic drop of NHUC in 2001 cannot be seen in AHCT.

Similar to the previous cases, Queensland has seen an increase in the number of houses under construction since 2002. This increase pushed the industry to go to its second phase in which the AHCT is directly related to NHUC. As can be seen in Figure 6-17, the NHUC and AHCT show the same trend in this period. Every peak and trough in NHUC is followed by peaks and troughs in the AHCT in this period.

With this explanation, it can be concluded that the workflow-based planning approach can precisely predict the behaviour of the Queensland house building industry. The capacity of the industry is 7,200 houses under construction, and the industry can produce this number of houses in 1.7 quarters on average. AHCT longer than 1.7 quarters signals the shortage of house building capacity and lack of housing supply in the housing market.

6.3.6 Australia

Australia is the final case in this study. This case was introduced as the meta case in the research design that sums all the previous cases and the remaining parts of the country. This case showed a similar trend to the other cases in the NHUC-AHCT relationship. The two phases of this relationship were shown by rectangular boxes in the previous chapter (Figure 5-18). In this chapter the industry's capacity is investigated by the estimation of the turning point between these two phases. In this regard the two phases are illustrated by the trend lines and the intersection of these trend lines shows the turning point.

To clarify the two phases, the transition area between them is again eliminated from the graph and the trend line for each of them is drawn. This transition area lies between 48,000 and 50,000 houses under construction. The following figure (6-18) shows the result of this analysis.

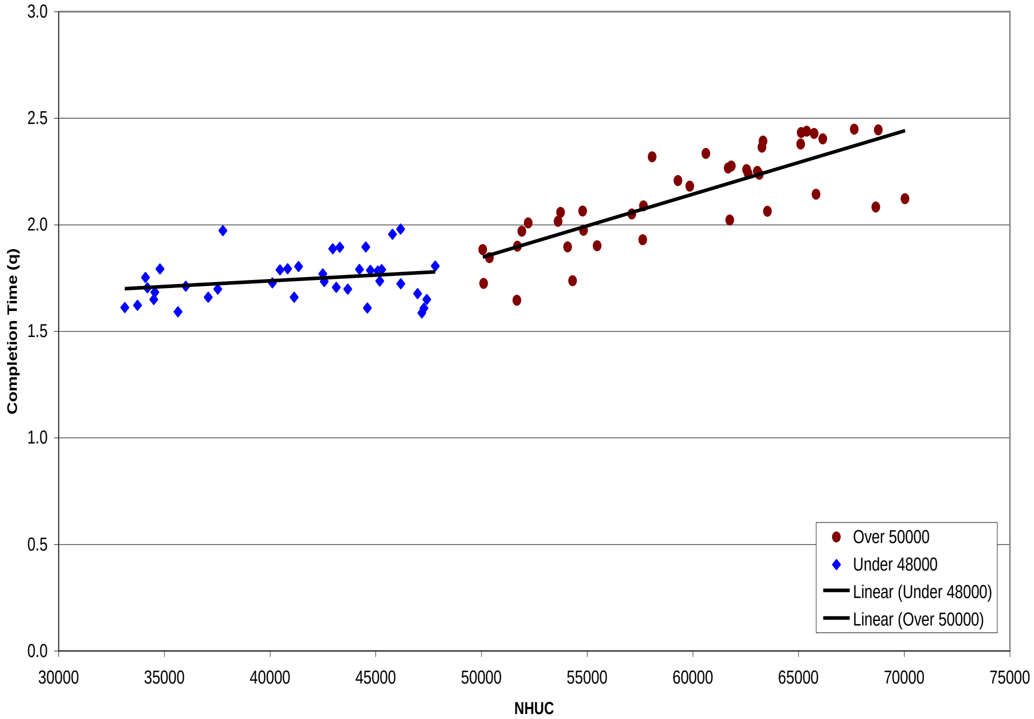


Figure 6-18: The trend lines for the two phases of the NHUC-AHCT relationship in Australia

To find the turning point between these two phases, the trend lines drawn in Figure 6-18 are extended to cross each other. Figure 6-19 demonstrates the result.

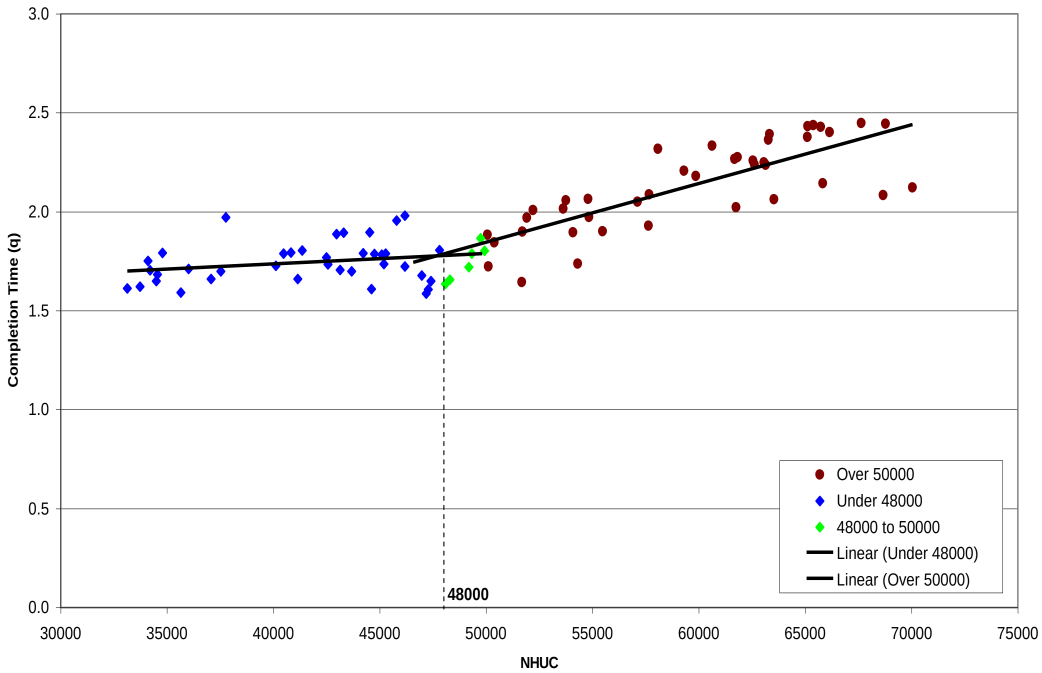


Figure 6-19: The critical NHUC in Australia

The data used for the trend lines are NHUC over 50,000 and under 48,000. However, the data points between these numbers are also shown in Figure 6-19 to demonstrate the trend lines covering this area.

As can be seen in Figure 6-19, the turning point is around 48,000 houses. This number of houses roughly suggests the capacity of the Australian house building industry. In this industry the data from last two decades show that whenever the number of houses under construction goes beyond this level, the completion time starts to increase. This increase is the result of the idle time in construction that results from the shortage of resources.

The minimum AHCT for this case is estimated by the average AHCT in the first phase which equals 1.75 quarters. This duration is an indicator of the behaviour of the industry and is used in the next sections.

Industry analysis:

To monitor the changes in the industry, the number of houses under construction and the average house completion time in last 20 years has been illustrated in the following figure. This figure also demonstrates the critical NHUC level and the average minimum AHCT. In this case they are 48,000 houses and 1.75 quarters respectively.

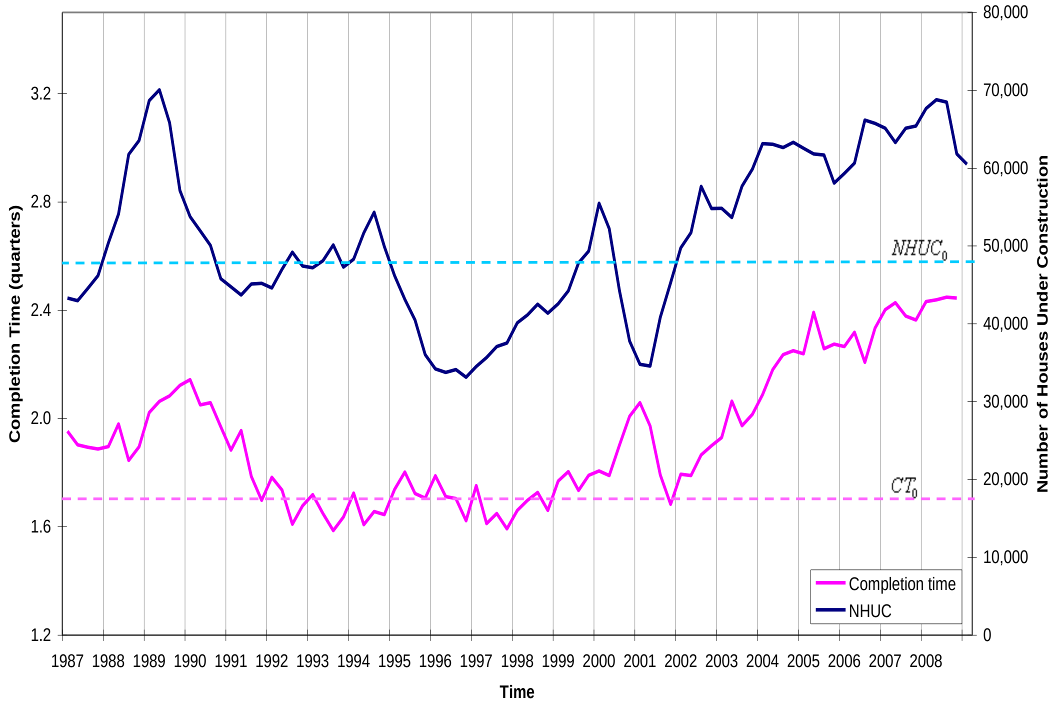


Figure 6-20: NHUC and AHCT trend in Australia

It has been explained in the theoretical understanding of the critical NHUC that whenever industry works under this level, the average house completion time is expected to be around minimum completion time, and whenever the industry exceeds this level the average house completion time is expected to grow.

As can be seen Figure 6-20, the NHUC was over critical level until 1991. Therefore, the average house completion time trend is expected to show AHCT longer than the minimum level. The AHCT graph in this figure shows that, in fact, the average house completion time was longer than the minimum AHCT in this period.

Next, NHUC declined to under the critical level and stays around it until 1994. As a result, AHCT remained around the minimum completion time. The peak point in mid-1994 returned a peak point in completion time. NHUC between 1995 and 2000 went below 48,000 houses. Therefore, AHCT trend is expected to show AHCT at the minimum level. The actual data shows that the average house completion time remained around minimum level in this period.

The growth of NHUC at the beginning of 2000 made the completion time increase and NHUC’s decline in 2001 made completion time decrease. Figure 6-20 shows that the house building industry has seen NHUCs over the critical level since 2002, and the completion time has never returned to its minimum level. By the end of 2008, the house building industry was working over its capacity.

With these explanations, it can be concluded that the workflow-based planning approach can explain the house building industry’s behaviour in this case. The capacity of the industry is 48,000 houses under construction, and average house completion times over 1.75 quarters indicate a shortage in house building capacity.

6.4 Chapter Summary

This chapter focused on the implications of the workflow-based planning approach in explanation of the house building industry’s dynamics. In this regard, the relationship between number of houses under construction and the average house completion time was investigated. This investigation was inspired by the work in process (WIP)-cycle time (CT) relationship in production planning.

According to the workflow-based planning approach, there are two phases in the relationship between WIP and CT in a production line. These two phases in fact are connected with a turning point which is called critical WIP. This part of research showed that a similar relationship exists between NHUC and AHCT in the house building industry. These two parameters have a two-phase relationship and these two phases are connected by a turning point, which was called critical NHUC.

The research estimated the critical NHUC for each case study and demonstrated that if NHUC goes beyond this point the average house completion time would be affected and would increase beyond its minimum level. Further, the average house completion time remains constant at the minimum level, if NHUC is under critical NHUC level.

The critical NHUC is also important because it shows the best condition for the industry in which the waiting time in the construction process is at the minimum level. It was also shown in this section that although the house building industry has a dynamic nature, its capacity remained almost constant in past two decades. This phenomenon was seen in all State cases and the national case of Australia.

The only State whose capacity could not be estimated was NSW. This was because the two phases of NHUC-AHCT could not be identified in this state. However, this was also explained by the workflow-based planning approach. According to this approach, the critical NHUC could not be determined in this State, because it has not reached the turning point in NHUC-AHCT relationship. This State built a significant house building capacity in the late 1980s and this capacity was never saturated since then. Therefore, it was always in its first phase of NHUC-AHCT relationship and did not go the second phase.

The critical NHUC and the minimum AHCT for the all States and the whole country is summarized in the following table (6-1).

Table 6-1: Critical NHUC and average minimum AHCT for Australia and different states

Case study	Estimated $NHUC_0$	$AHCT_0$
Australia	48,000	1.75
Victoria	10,700	1.8
Western Australia	5,300	1.7
South Australia	3,200	1.7
Queensland	7,200	1.3

The critical NHUC and minimum AHCT were investigated in this chapter to show how the workflow-based planning approach can be used for the explanation of the Australian house building industry behaviour using these two parameters.

The workflow-based planning approach suggests that when the industry works over its capacity (critical NHUC), the completion time has a direct relationship with NHUC and grows over its minimum level. Therefore, AHCTs longer than the minimum level signal a shortage in house building capacity and consequently a shortage in the housing supply.

This approach was investigated in all cases. It was shown in all the cases that the critical NHUCs estimated for them are the actual turning point in the behaviour of the industry and they can be considered as the industry capacity. Further, the minimum AHCTs estimated in this chapter were suggested as the indicators of the industry state of house building capacity and housing supply. AHCTs over the minimum level signal an industry over capacity and AHCTs around minimum level indicate the availability of sufficient capacity in the industry.

By the end of this chapter, the analysis at the industry level was fulfilled and the first three objectives of the research were addressed. The following chapter focuses on house completion time at the company level and explores the implications of the workflow-based planning approach for the improvement of the actual house building processes.

7 CHAPTER SEVEN - WORKFLOW MODELLING AND WORKFLOW-BASED PLANNING IMPLICATIONS FOR HOUSE BUILDERS

7.1 Introduction

The previous chapters investigated house completion time at the industry level. This included the investigation of effective parameters on average house completion time, the applicability of Little's law, and the relationship between average house completion time and number of houses under construction. Further, the critical number of houses under construction and house building capacity of the industry was estimated using the workflow-based planning approach, and house completion time was proposed as an indicator for the state of capacity.

However, the workflow-based planning implication is not limited to the industry analysis. The use of this approach at the company level for individual house builders is suggested by many researchers. To explore these implications on house completion time, the house building process needs to be modelled and different operation scenarios simulated.

This chapter starts with the modelling of construction in a production building process, and describing the specifications of the model and its abilities are discussed. This model is then used as a basis for further understanding the process and analysing different operational strategies. Theses analyses are undertaken using simulation. The main aim of the chapter is to explore some main factors affecting house completion time. Further, relevant factors, such as resource utilization and capital tie-up in the process, are also considered.

The analysis commences with an investigation of the effect of workload on house completion time. In this regard, the number of houses under construction is used as an independent variable and its effect on the completion time is monitored. Then, the construction commencement interval is studied and it continues with an exploration of the effect of house design options on completion time.

Following sections are the detailed explanation of the case study and the model's specifications, some definitions and assumptions considered in the simulation, and the analysis and investigations.

7.2 The sample house building production

The residential construction process used in this research is a production building operation. This operation aims at building typical transportable houses on-site and transporting them to their final location. The construction activities in this operation are continuous. The whole process consists of 23 activities, which are listed with their related durations in Table 7-1. These durations were obtained by observation and interviews at the construction site with sub-contractors and the site manager. The activity durations are generally the most probable time needed for completion of the activities.

Table 7-1: Construction process activities and their durations

Activity number	Activity	Duration (day)
1	Floor Slab	1
2	Wall Framing	1
3	Wall Cladding	2
4	Electrical Rough In	1
5	Plumbing Rough In	0.5
6	Roof Trusses	0.5
7	Roofing	1
8	Insulation	0.5
9	Gyprocking (Plastering)	1
10	Joint Finishing	2
11	Cornicing	1
12	Sanding	1
13	2nd Fix Carpentry	2
14	Kitchen Fitting	1
15	Tiling	4
16	Painting	5
17	Electrical Fit Out	0.5
18	Plumbing Fit Out	0.5
19	Shower Screen	0.5
20	Carpeting	0.5
21	Cleaning	1
22	Transportation	2
23	Commissioning	1

The whole construction process is illustrated in Figure 7-1. Most of the activities are undertaken sequential, although there are some concurrent activities. The construction of each house starts with floor slabbing and finishes with commissioning.

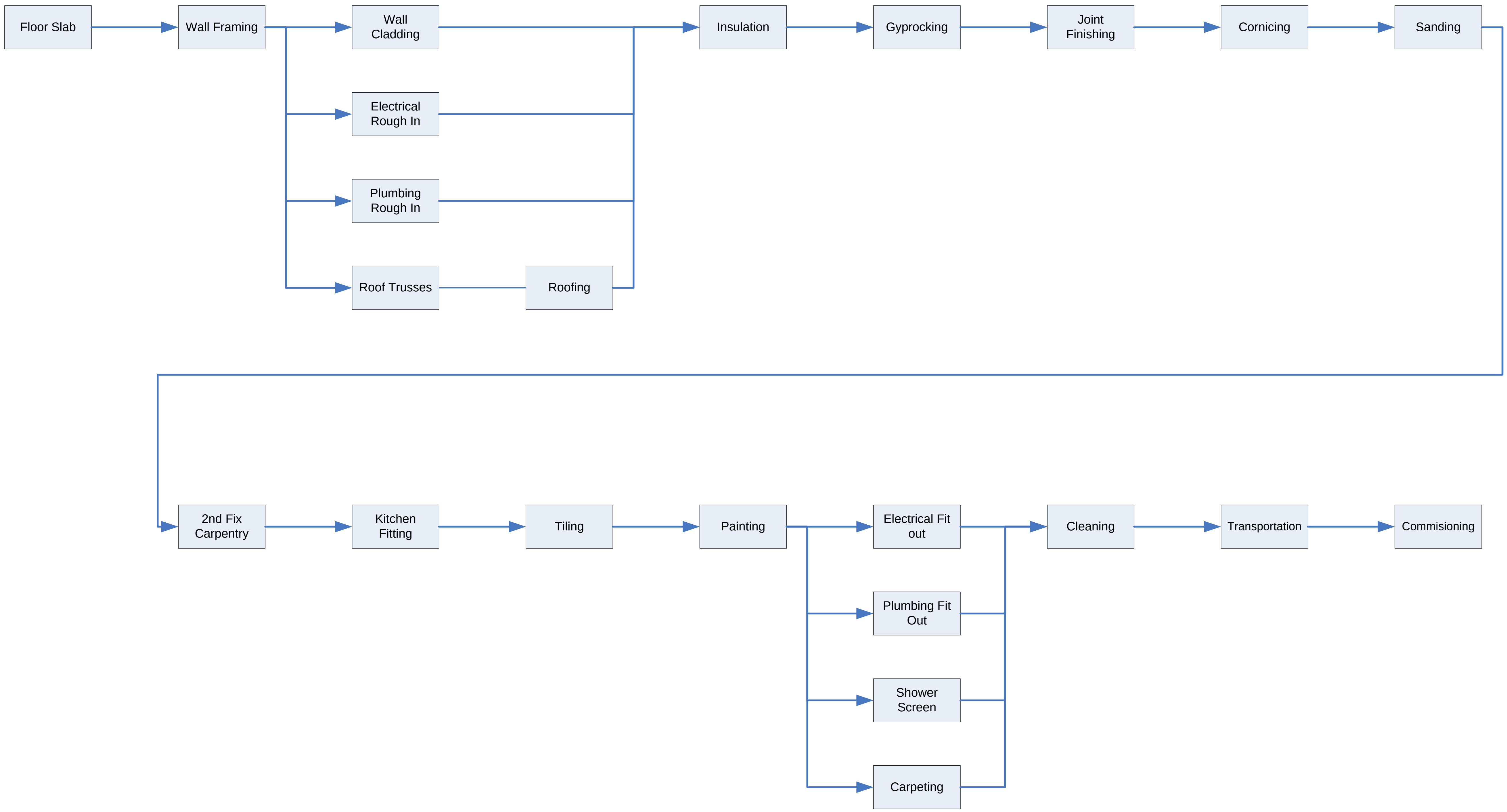


Figure 7-1: Schematic of the production building process

Construction is undertaken by 18 sub-contractors and/or crews. In this operation, similar activities can share the same resources. For example, the floor slabbing, wall framing and wall cladding are done by two teams of carpenters. This kind of resource allocation has been considered in the modelling of the process. The sub-contractors and crews in this operation consist of:

- Carpenter
- Electrician
- Plumber
- Roofer
- Insulator
- Gyprocker (Plasterer)
- Joint Finisher
- Cornicer
- Sander
- 2nd Fix Carpenter
- Kitchen Fitter
- Tiler
- Painter
- Shower Screen Installer
- Carpeter
- Cleaner
- Transporters
- Commissioner

7.3 Modelling

Palaniappan et al.(2007) suggest that to model a generic construction process and capture the workflow characteristics, four constructs should be considered. These constructs are: 1) generating a set of work item per time period; 2) computing the number of work items per time period at any downstream step; 3) work in process; 4) number of work items waiting for a resource. In addition, the model developed in this research possesses other constructs and specifications such as computing the completion time, activity durations, and relationships and resources. Figure 7-2 illustrates a schematic of the model including all the constructs, activities, relationships and resources.

Generating a set of work items per time period

This construct produces work items per time period. In the case of residential construction, this part of the model should be capable of managing the commencement of construction. These commencements can follow a uniform pattern: for example, a number of houses per week; or can follow a probabilistic distribution; or they can be random. In any case, this construct should be able to generate and control that behaviour in the model.

Whereas the main focus of this research is on construction commencement, this construct is highlighted in the model with the capability of control on the number of houses for production, assigning different house design options and being a cost centre in the production alongside of control of construction commencement intervals. The first component in Figure 7-2 is this construct.

Computing the number of work items per time period at any downstream step

Workflow variability is an important parameter in operation management. It can affect the utilization of the resources and cycle time. This variability can be calculated by counting the number of work items before or after a process per time period.

Work in Process (WIP)

This construct counts the number of work items in the production process, or the number of houses under construction (NHUC). This includes the houses which undergo the construction, and the ones waiting for the resources. WIP is the main indicator of the project holding cost. WIP can also work as a control for the process and affect the variability and smoothness of the production. Therefore, the model designed for this research must be capable of calculating and controlling the WIP. The second component in the model (Figure 7-2) is the WIP controller.

Number of work items waiting for a resource

Finding an effective operational strategy is impossible without knowing the bottlenecks in the process. These bottlenecks can be identified by the number of work items waiting before a process component. In production building, the number of the waiting work items is known as number of idle houses. Knowing the amount of investment for starting a new construction, this idle time can be a source for an increase in the holding cost of the project. Therefore, another construct embedded in the model is calculation of number of idle houses. In Figure 7-2, this component is located before each activity.

Computing completion time

This construct calculates and records the completion time of the houses. This time included the waiting times and the time of construction. The last component in Figure 7-2 plays the role of this construct.

Activity durations and relationships

The activity durations in this model are derived from the pilot production building. However, the model is capable of assigning different probability distributions to the activity durations.

This can help the analysis of the effect of variation on the operation. Moreover, the activity components can have different durations due to different options of houses.

The relationships between the activities are based on the actual process demonstrated in Figure 7-1.

Resources

The resources in this model consist of human resources. These resources are according to the sample production building mentioned in Section 7.2. The components representing the resources are shown in Figure 7-2. As can be seen in this figure, the number of resources is less than the number of activities. This is due to the resources allocated to different activities. For instance, electrical rough in and fit out are undertaken by the same crew of electricians.

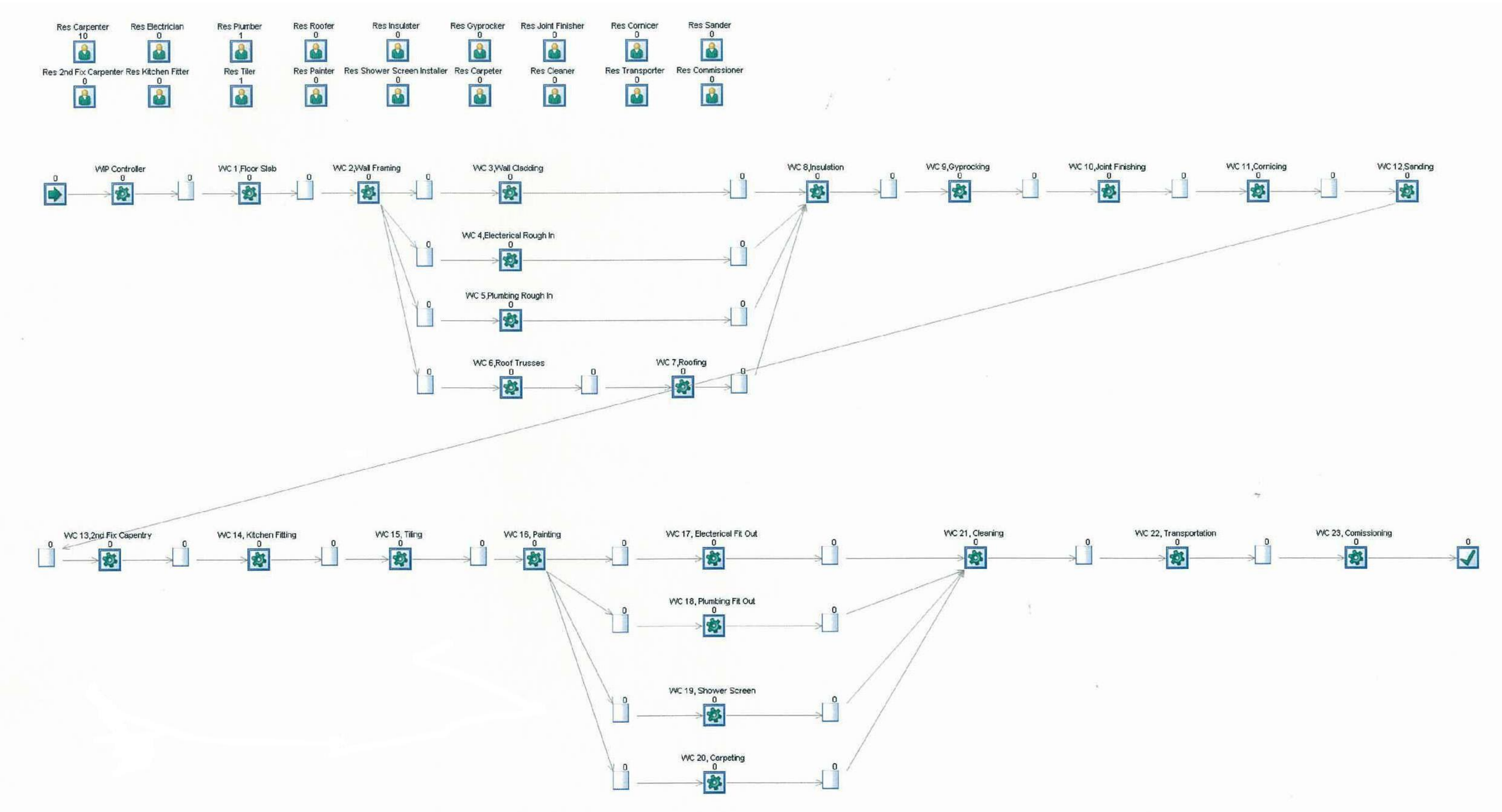


Figure 7-2: The model of a production house building operation

7.4 Definitions and assumptions

There are some terms and assumptions used that can affect the understanding of the results. The following are used in this research:

- *Project* in this study refers to the construction of a specific number of identical houses; *Project duration* to the duration of all houses;
- *Completion time* refers to house completion time;
- *Commencement interval* refers to the time between two successive construction commencements;
- *Commencement interval decision* is the decision determining the commencement interval duration, which is assumed to remain constant during the project;
- *Job* refers to work undertaken by a particular crew;
- *House design option* is a specific design, which is offered by the production builder; *;*
- *Resources* refer to human resources alone.

Further assumptions underpinning this model are that there is only one crew available for each activity, and that these do not change during the project in terms of size or productivity.

7.5 Number of houses under construction and house completion time relationships

Hopp and Spearman (2008) in their book "Factory Physics" argue that one of the main controllers of cycle time in a production operation is work-in-process (WIP). They show that a constant level of WIP leads to a constant cycle time. Therefore, a smooth production line with a constant cycle time can be achieved by controlling the number of works in the process.

WIP in house building equals the houses under construction. This includes the houses in which a construction activity is being undertaken and the houses waiting for resources. Cycle time in a house building process is house completion time. Therefore, assuming the house-building process works similarly to a production process (Willenbrock, 1998), a smooth house production with a constant completion time hypothetically can be achieved by controlling the number of houses under construction.

This part of the research investigates this hypothesis. Modelling of a production house building process is employed. A production scenario, in which the number of houses under construction (NHUC) is controlled and constant, is simulated, and the completion times of the houses are monitored. This production building initially models the production of one option of house. This is due to the effect of house type variation on the results of the study. This effect is investigated later in this chapter (Section 7.7).

The activities, their durations, and the detail of the house building process were explained in the previous chapter (Section 7.2). A schematic of the model was illustrated in Figure 7-2. However, the WIP controller component of the model is shown in Figure 7-3. As can be seen in this figure, this controller is located between the work entry component and the first activity of the construction process. This prevents the process from having more jobs while it is working under a specific workload.

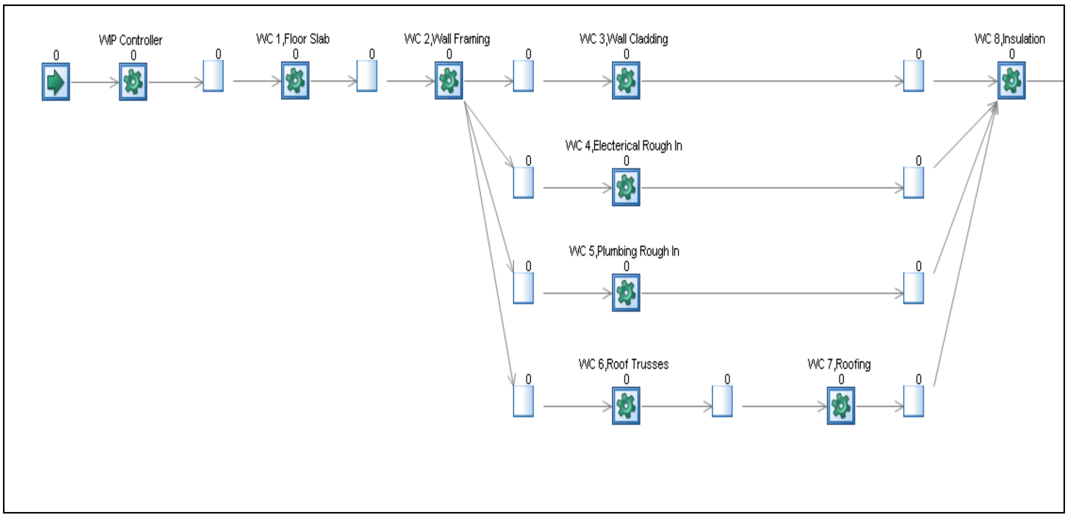


Figure 7-3: Part of the model showing WIP or NHUC controller

To investigate the effect of NHUC on house completion time, different levels of NHUC are simulated and house completion time monitored. The level of NHUC is decided before each simulation and remained unchanged during the simulation. The simulations were undertaken with NHUC between one and ten, and some of the results are shown in Figure 7-4.

The results of these simulations show that house completion time remains constant for the whole period of production. For instance, the results of four, six and eight houses under construction are illustrated in Figure 7-4. Other NHUC levels show the same trend for the house completion time.

So far, it was shown that if a house builder uses a workflow control between the sales department and construction process, the completion time indirectly is controlled and becomes predictable. Knowing that the conventional practice in the residential construction industry is direct control on each activity and sub-contractor, this finding helps the industry have smooth production using a single control point for the workflow, avoiding too many controls and too much management input.

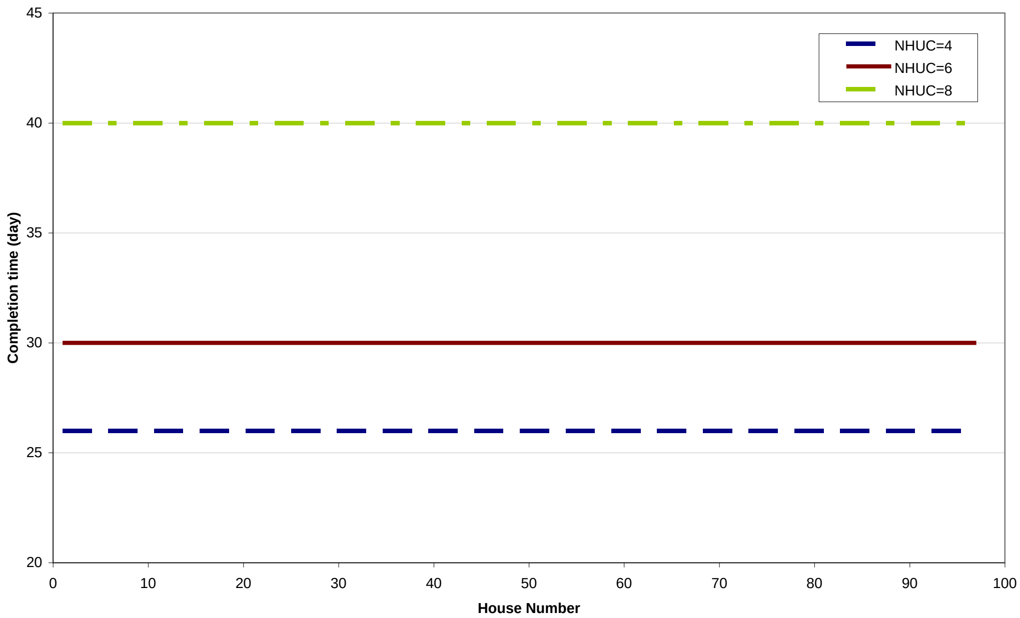


Figure 7-4: Completion time of houses during the production period with different NHUC level

Figure 7-4 also demonstrates that construction of the same type of house with different level of workload takes different amount of time. The completion time in this case is 26 days with four houses under construction, and it is 30 days with six houses. To show this more clearly, the completion time for all of the NHUC scenarios is illustrated in Figure 7-5.

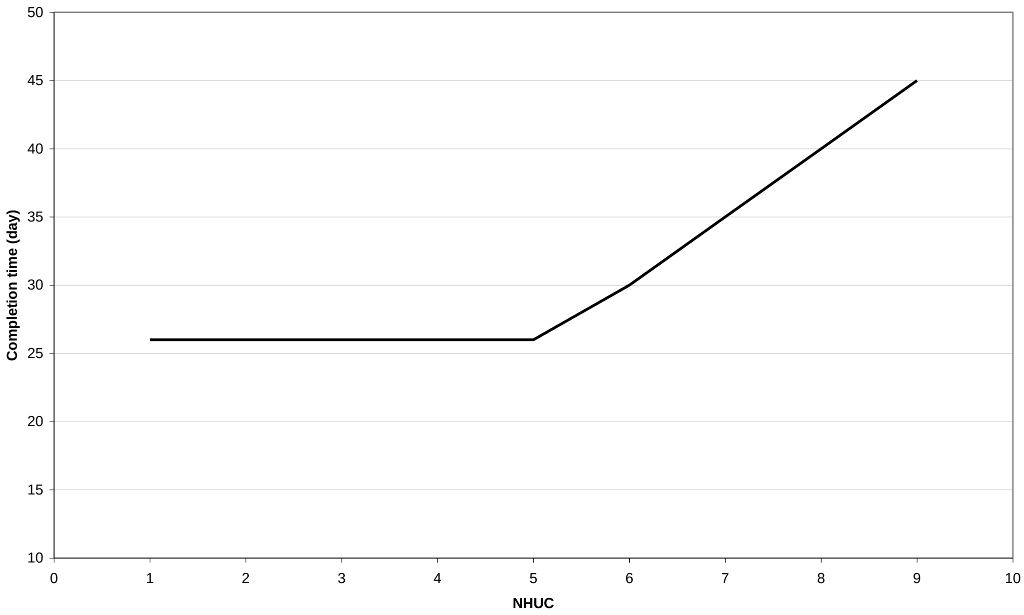


Figure 7-5: NHUC-Completion time relationship

As was explained in Chapters two and six (figures 2-1 and 6-1), the workflow-based planning approach suggests a two-phase relationship between WIP and cycle time. The turning point between these two phases is called critical WIP. The cycle time is at its minimum level when production has workload of less than critical WIP, and it has a direct relationship with WIP when the workload is over the critical level.

It was shown in Chapter six that, similar relationship exists between number of houses under construction and average house completion time at the industry level. Figure 7-5 illustrates that the same kind of relationship between number of houses under construction and house completion time can be seen at company level. In this study, the critical number of houses under construction is five houses. Under this level, the completion time is equal to 26 days which is the minimum time needed for construction of this house. The increase on number of houses under construction over this level makes completion time grow.

Note that the consistency of completion time is different from having optimum (minimum) completion time. As mentioned earlier, constant NHUC produces constant completion time. However, this time may not be the minimum time needed for the completion. For example, in this study, keeping the NHUC at eight houses would keep the completion time at 40 days (Figure 7-4). But this time is 14 days longer that the minimum completion time (26 days). That means houses in this production scenario have to spend 14 days sitting idle and waiting for resources, which will be added to the overall completion time.

Section summary

The workflow-based planning approach suggests that one way to control the cycle time is to control WIP. To investigate this in the house building process at company level, an actual production house building was modelled; different levels of WIP, or NHUC in housing terms were simulated and house completion time monitored.

The result showed that when NHUC is constant, house completion time is constant and therefore, predictable. This can help builders to implement a workflow controller between the sales department and construction process. The output of this controller would be a smooth production line without the need for close control on each activity and sub-contractor.

Further, the relationship between completion time and NHUC was explored. It was shown that the NHUC below the critical NHUC level does not affect the completion time, while above this level it has a direct effect on completion time.

The next section moves the research focus to construction commencement and explores the consequences of changes in construction commencement intervals on house completion time.

7.6 Construction commencement intervals and house completion time

In the previous section, it was shown that the existence of a workflow control at the beginning of construction process can control the completion time. This section continues this investigation and explores another type of control that can be implemented at the beginning of the construction process. This control is the construction commencement intervals.

The importance of construction commencement intervals in the house building industry is usually ignored by project managers. In the case of large residential contractors, the commencement of construction for each house is decided based on the contract of sale and availability of the first crew that starts construction. Therefore, as soon as conditions for the start of a new job are met and there is an order for the house, construction starts.

However, residential construction does not simply consist of a single activity. It includes many activities with their related essential human and material resource limitations. These activities affect each other as well as the whole process of construction. It means that the start of a new house can affect the whole construction operation, and scheduling of start should be decided with the consideration of the whole process, not just the first activity of the process.

This part of the research shows the importance of construction commencement decisions. To address the main concern of the research about house completion time, the effect of this decision on the completion time is addressed. Further, the research explores the effects of commencement intervals on a house-building project duration, resource utilization and number of houses under construction.

For this purpose, the same model used in the previous section and explained in Chapter seven is used. A house-building project of 200 houses is employed as a benchmark to compare different commencement interval scenarios, enabling an analysis of the resultant operations.

Construction commencement intervals scenarios

The decision to commence construction, and the interval between commencements, is the starting point for the operation. House building operation, like any other operation, can be influenced by this decision. Determining this influence, and to what extent it affects completion time, is the subject of the following sections.

In this regard, different scenarios for commencement intervals were used and other parameters (like completion time, project duration, resource utilization and number of houses under construction) were monitored against these scenarios. The reasons for selecting these parameters and the way that they affect the project's success are explained at the beginning of each related section. It should be noted that construction commencement refers to the start of the construction of each house.

The scenarios for commencement intervals range from 1 day to 10 days. The commencement interval is a part of project planning and is decided before the project starts. This means the intervals remain unchanged during project implementation. It is assumed that the intervals keep constant during the project.

The first parameters that are investigated against different commencement interval scenarios are project duration and house completion time.

Project duration and house completion time

Project duration is always one of the main concerns for a project manager. Extension of this duration can result in an unbearable overhead or penalty for the project and loss of reputation for the contractor. In production building, decreasing the project duration can be another incentive for the project manager to push the production operation. It seems logical to think that if construction starts sooner, it would be finished sooner, and consequently the project duration would be shorter.

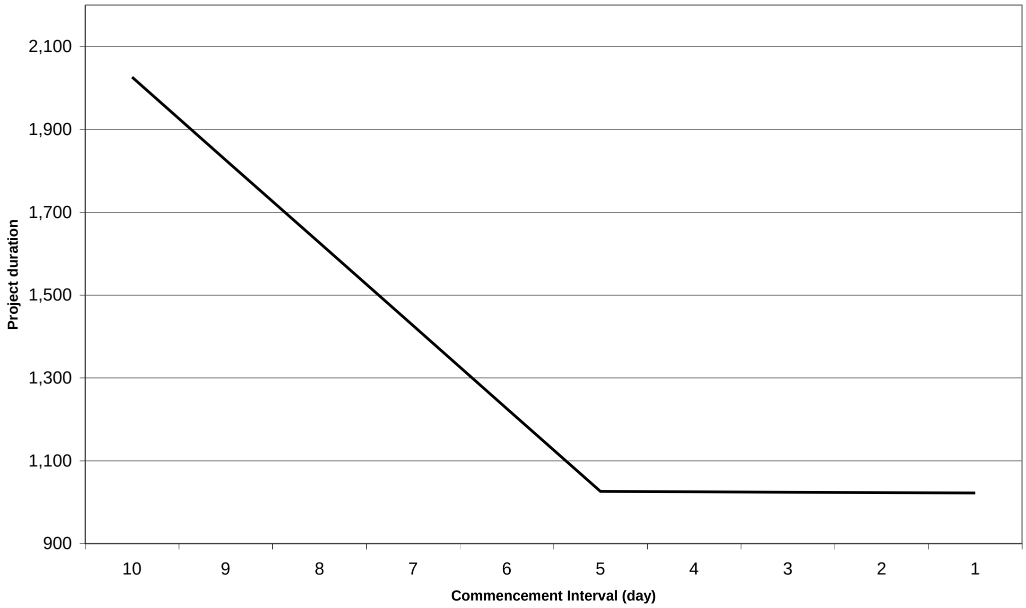


Figure 7-6: Project duration in different commencement intervals scenarios

Verification of this perception led to an investigation of the effect of commencement interval on the project duration. Figure 7-6 is the result of this investigation. This graph shows that the project duration shortens if the intervals decrease up to an interval of 5 days. But it keeps constant after this point. This means the perception that a sooner start results in a sooner finish can only be true to some extent. The shortening of the intervals can affect the project duration and make it shorter, but this loses its effect after some point. In this case, a 5 day interval is the point at which shortening of the intervals loses its effect.

Beside the project duration, house completion time also affects the project's success. Completion time is an important factor in holding cost and cash flow of the project. Longer completion time means a slower return of investment and higher holding cost for the project. This part of the research clarifies the impact of commencement interval decisions on completion time. For this purpose, the completion time of each house is derived from the simulation and illustrated in Figure 7-7.

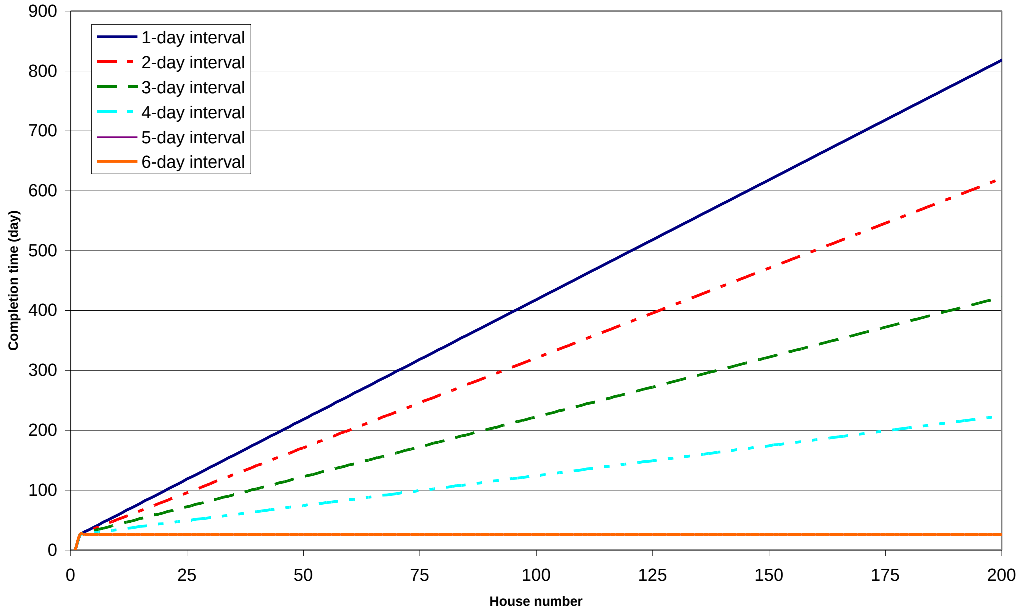


Figure 7-7: Completion time for each house in different commencement interval scenarios

In Figure 7-7, the horizontal axis is the house number and the vertical axis is completion time. For example, this graph shows that it takes 300 days for house number 75 to be completed in a 1 day commencement interval scenario. Knowing that construction of a house can be completed in 26 days (less than a month), in the extreme case the completion time for house number 200 which takes 800 days (more than 2 years) clearly shows the disastrous effect of pushing a house building operation to have more jobs commencing as soon as possible.

Figure 7-7 shows that lengthening commencement intervals shortens the completion times. This trend goes on up to the 5 day intervals where it reaches the minimum level. However, these intervals do not only affect the completion time, but also affect the project duration. Figure 7-6 showed that as long as the intervals are under 5 days, lengthening the intervals does not harm the project duration. But intervals longer than 5 days extend the project duration. Therefore, considering both Figures 7-6 and 7-7, it can be concluded that the best interval for this particular project, an interval which can keep the completion time and project duration at a minimum, is 5 days.

Resource utilization

As described above, one of the reasons for project managers starting a new house is the availability of work crews. An available crew is one without a job but ready to work. This availability is costly for the contractor. Therefore, one of the responsibilities of a project manager is to keep the crews busy, and therefore, increase resource utilization. In this regard, project managers, whenever possible, start new construction and push the production process.

To investigate the level of utilization, it is assumed that all the crews are employed in-house by the general contractor. Their contracts start on the first job assignment and finish on the completion of the last job. It should be noted that a job refers to the activity performed by the crew and does not mean the construction of the whole house. With this assumption, if a special crew needs 1 day to finish its job and the project consists of 200 houses, it has to work for 200 days during the project. In this case, if the crew is employed for 400 days, the utilization would be 200 days out of 400 which means 50 percent.

Figure 7-8 shows the utilization of some of the crews in different commencement interval scenarios. This figure clearly shows that shortening the commencement interval leads to an increase in utilization. Therefore, from a utilization perspective it could be a beneficial decision for the project manager to push the house building process and start new houses with shorter commencement intervals.

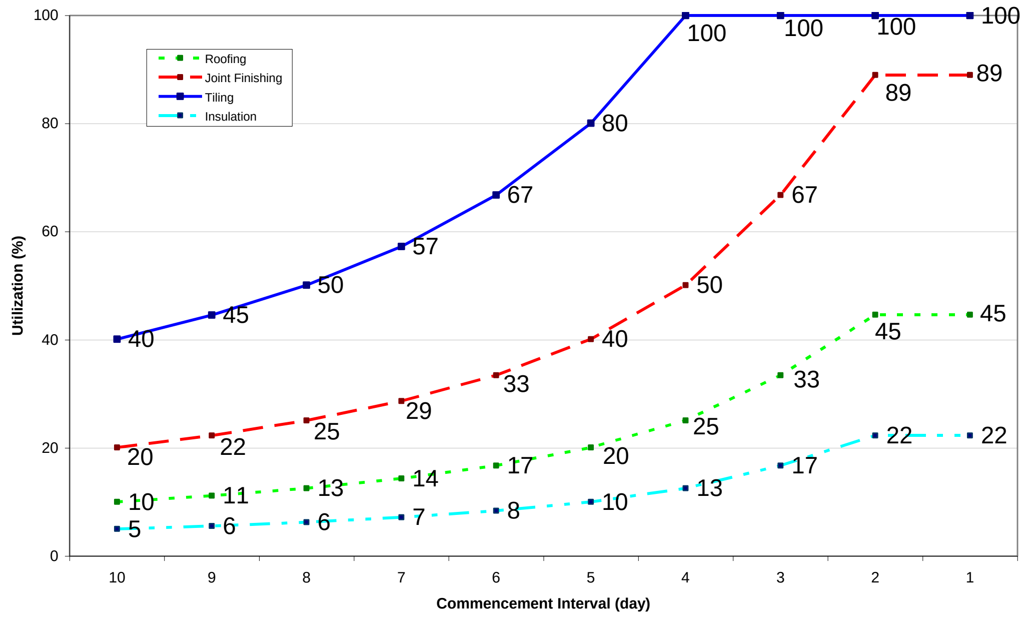


Figure 7-8: The resource utilization for some of the crews in different interval scenarios

In addition to the trend of utilization, Figure 7-8 shows that there is a maximum utilization for all four activities. The graph shows 100 percent utilization for the tiling activity with the commencement intervals equal to or less than 4 days. But the maximum utilization for roofing is about 45 percent. It means pushing the production line with shorter commencement intervals can increase the utilization of the resources but it loses its effect at some point in time. Therefore, there are other parameters in the production line that affect resource utilization and prevent it from reaching 100 percent.

The existence of this maximum utilization can be insightful for managers. This maximum level can be crucial for an activity like insulation where it reaches 22 percent utilization (Figure 7-8). For an activity with only 22 percent utilization, the best decision could be outsourcing. Therefore, it can be concluded that although faster commencements or shorter intervals can increase the utilization, there is a limitation to this utilization. This provides information to project managers, allowing them to recognize which resources are poorly utilized, and to decide to outsource that work.

Further, it should be recalled that 5 days is the optimum commencement interval for producing the minimum project duration and house completion time. This interval prevents the construction operation from reaching its maximum resource utilization (Figure 7-8). Therefore, a trade-off should be made between completion time/project duration and resource utilization.

Number of houses under construction

Long completion time can be very disadvantageous. However, knowing how it is disadvantageous and to what extent, is not clearly understood. It is clear that a house under construction represents a case where capital has been invested but the income has not yet been realised. Therefore, more houses under construction means more investment funds tied up and more finance cost.

Figure 7-9 shows the effect of decreasing the intervals between each construction commencement on the number of houses under construction. The horizontal axis in this figure is time and the vertical axis is NHUC. The graphs show the number of houses under construction for each day of the project. The project is complete when there are no more houses under construction and the graph reaches zero NHUC.

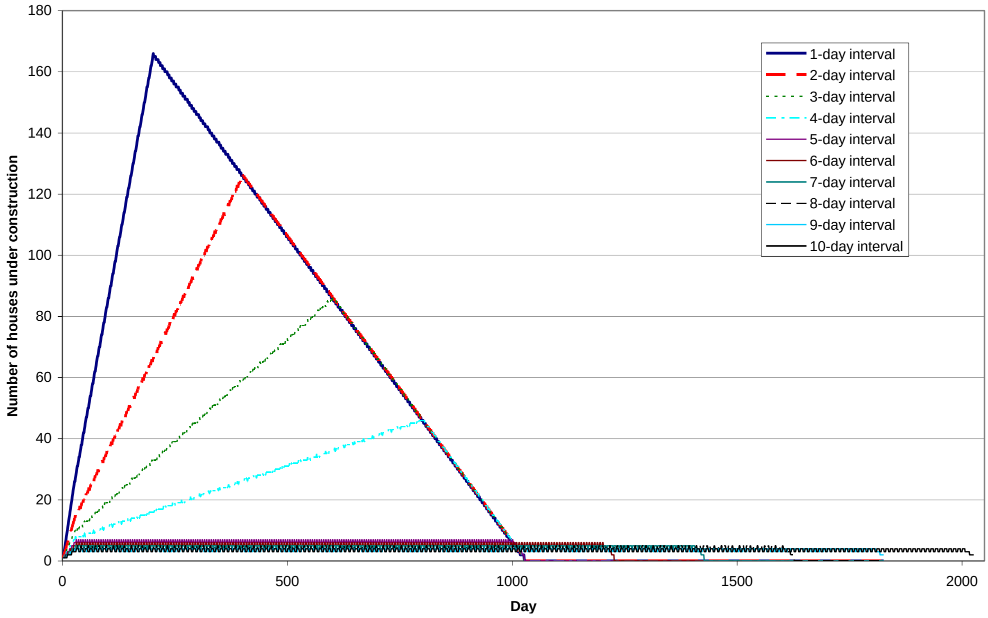


Figure 7-9: Number of houses under construction during the project

Simulation of 1 day intervals shows that there is a time when there are more than 160 houses under construction, which requires significant investment. The upward slope in Figure 7-9 shows the rate of construction commencement and the declining slope of the graphs represents the completion rate. The higher rate of commencement or steeper upward slope does not lead to a higher rate of completion; instead, the completion rate keeps constant for intervals between 1 day and 5 days. Based on this figure, the result of pushing the production line to start new construction faster is a higher NHUC.

The project's capital cost is a function of duration and volume of investment. Figure 7-9 shows that a decrease in commencement intervals results in an increased volume of investment. At the same time, this decrease makes the completion time or investment time longer (Figure 7-9). Therefore, with larger volume and longer time of investment, it can be concluded that the direct consequence of shortening the intervals is an increase in capital cost.

Note that the minimum project duration and completion time could be achieved by a 5 day interval. This interval could also maintain the NHUC at the minimum level. Looking at the activity durations shows that the longest activity is painting with duration of 5 days (Table 7-1). This is the activity which dictates the production rate, and consequently the finish date of the project, and the best interval rate for reaching maximum profit. Therefore, it can be concluded that the construction commencement decision in the house building process should be decided based on the slowest activity.

Section summary

In the house building industry the commencement of construction is usually decided based on the existence of an order and availability of the related crew for the first activity. These two preconditions for construction commencement ignore the rest of the construction process and the limitations of resources and activities. On the other hand, reaching for higher resource utilization, and the mistaken perception of a “sooner start-sooner finish”, encourage project managers to start the construction of houses as soon as it is possible. This research showed the result of this perception on the house building process and the importance of the commencement decision.

It was demonstrated that a shorter interval can increase the utilization of the resources but this utilization has a limitation and, in many cases, the resources do not reach 100 percent utilization. In fact, there is a maximum possible utilization for all resources. This maximum utilization can be a decision making point for outsourcing.

The perception of “sooner start-sooner finish” was also investigated. The simulation of shorter than 5 day commencement intervals showed a constant project duration. Therefore, the perception of “sooner start-sooner finish” is correct only in very limited circumstances. In the model examined for this research, the perception holds where the commencement intervals are longer than 5 days. If the intervals become shorter than 5 days, the perception is inaccurate and adds to delays in completion times. In addition, monitoring the number of houses under construction during the project proved that the shorter intervals could be disastrous for the contractor instead of being beneficial.

The common point between different parts of these analyses was the importance of the production rate of the slowest activity; in this case 5 days. It has been shown that if the commencement interval is decided based on the slowest activity, the minimum project duration and completion time and minimum capital cost will be achieved. Therefore, finding the slowest activity is vital for the project manager in house building process. The construction commencement decision should be decided based on the slowest activity and not the availability of the first crew or existence of a construction order.

So far, the effects of number of houses under construction and construction commencement intervals on house completion time have been demonstrated. The next section investigates the effect of house design variations on the completion time.

7.7 House design options and house completion time

Hopp and Spearman (2008) divide variation in an operation into two categories; **controllable variations** which are a direct result of decisions, and **random variations** which are a consequence of events beyond our immediate control. This research aims at helping house builders improve their operations using simple and effective decisions. Therefore, it focuses on the controllable variations.

House design options are a controllable variation that is determined by a house builder. This variation is a common practice in the house building industry. Particularly, in a competitive housing market, builders try to offer different design options to attract more customers. Alternatively, they might decide to change their design and offer smaller houses to achieve shorter completion times and serve more customers.

In both of these scenarios, builders strive for improved corporate performance by offering more variations. This research investigates the impact of variation resulting from offering different house options on completion time, and thereby aims to assist house builders to understand the house building process better. Since these two scenarios return different results, they are considered separately. In both scenarios, it is assumed that the production builder currently has smooth production. This smooth operation is demonstrated and explained first, and then the result of introduction of new house options, is discussed.

This investigation is based on the modelling a house building operation explained earlier. Different scenarios of house options are simulated and the results compared. The following sections include the simulation of standard production, introduction of a larger house option, and introduction of a smaller house option.

7.7.1 Simulation of standard option

Initially a basic production house of one-option is simulated. The activity durations for this option are detailed in Tables 7-1 and 7-2. The completion time of the standard house option (Figure 7-10) demonstrates that one-option production produces smooth constant completion time. In this operation, the completion time is equal to the minimum time needed to build house Option A.

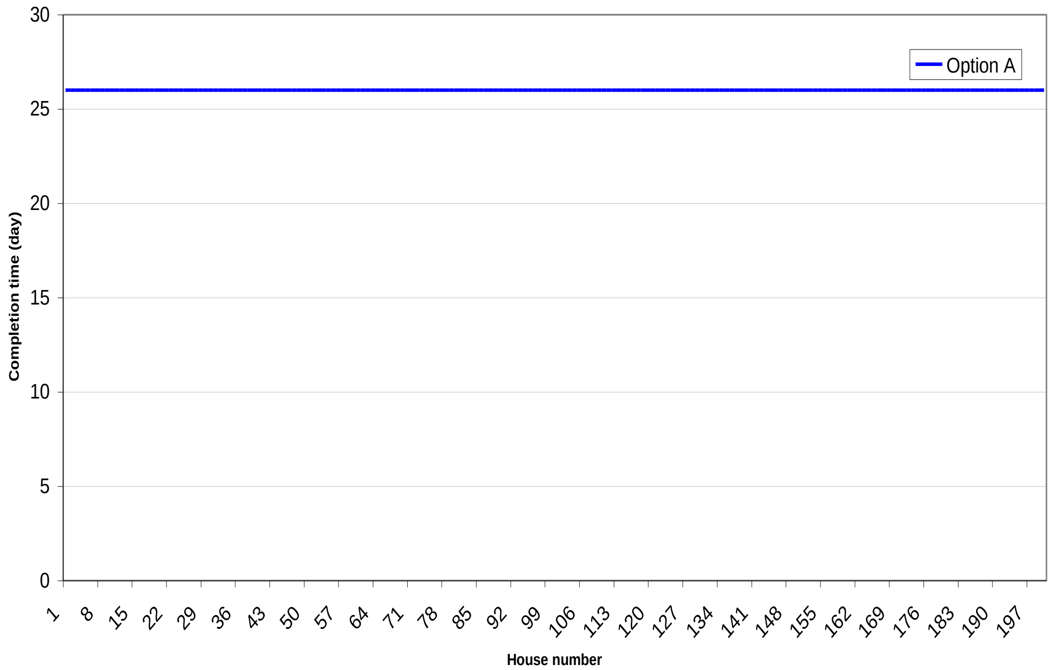


Figure 7-10: Completion time for Option A in one-option production

In this scenario, it is assumed that the commencement interval is decided prior to the introduction of new option. This commencement interval is the one at which the current production operates smoothly. Within this smooth operation, all houses are built in a consistently specific time.

Now that the variation of commencement interval is eliminated from the system, it is possible to see the effect of having different house options on the operation, and specifically on completion time. It should be noted that factors such as resources availability, process structure and activity relationships are assumed to remain unchanged during the production period.

7.7.2 Introduction of a larger house option

This scenario investigates the situation in which a production builder decides to introduce a larger house option to the production process. In this case, larger house means a house which needs longer activity durations, and as a result, has a longer completion time than the standard house option.

The activity durations for the new options are derived from Option A with variations of 5 percent. This level of variation is relatively small; however, as the aim of the research is to clarify the relationship between variation and completion time, this small 5 percent increment was utilized. Table 7-2 shows the activity durations for four house options of B, C, D and E. The activity duration for each option is 5 percent longer than the previous one.

Table 7-2: Activity durations for different options of houses

Activity \ Option	A	B	C	D	E
Floor Slab	1	1.05	1.1	1.15	1.2
Wall Framing	1	1.05	1.1	1.15	1.2
Wall Cladding	2	2.1	2.2	2.3	2.4
Elec. Rough In	1	1.05	1.1	1.15	1.2
Plum. Rough In	0.5	0.525	0.55	0.575	0.6
Roof Trusses	0.5	0.525	0.55	0.575	0.6
Roofing	1	1.05	1.1	1.15	1.2
Insulation	0.5	0.525	0.55	0.575	0.6
Gyprocking	1	1.05	1.1	1.15	1.2
Joint Finishing	2	2.1	2.2	2.3	2.4
Cornicing	1	1.05	1.1	1.15	1.2
Sanding	1	1.05	1.1	1.15	1.2
2nd Fix Carp.	2	2.1	2.2	2.3	2.4
Kitchen Fitting	1	1.05	1.1	1.15	1.2
Tiling	4	4.2	4.4	4.6	4.8
Painting	5	5.25	5.5	5.75	6
Elec. Fit Out	0.5	0.525	0.55	0.575	0.6
Plum. Fit Out	0.5	0.525	0.55	0.575	0.6
Shower Screen	0.5	0.525	0.55	0.575	0.6
Carpeting	0.5	0.525	0.55	0.575	0.6
Cleaning	1	1.05	1.1	1.15	1.2
Transportation	2	2.1	2.2	2.3	2.4
Commissioning	1	1.05	1.1	1.15	1.2

The next step is to add variation to the system. For this purpose, the production period of 2,000 days is considered and Option B is added to the production process. This production period is an assumption that does not affect the result of the simulation, but it needs to be assigned to limit the simulation duration. Figure 7-11 demonstrates the result of two-option production. In this graph, the horizontal axis is the house number and the vertical axis is the completion time.

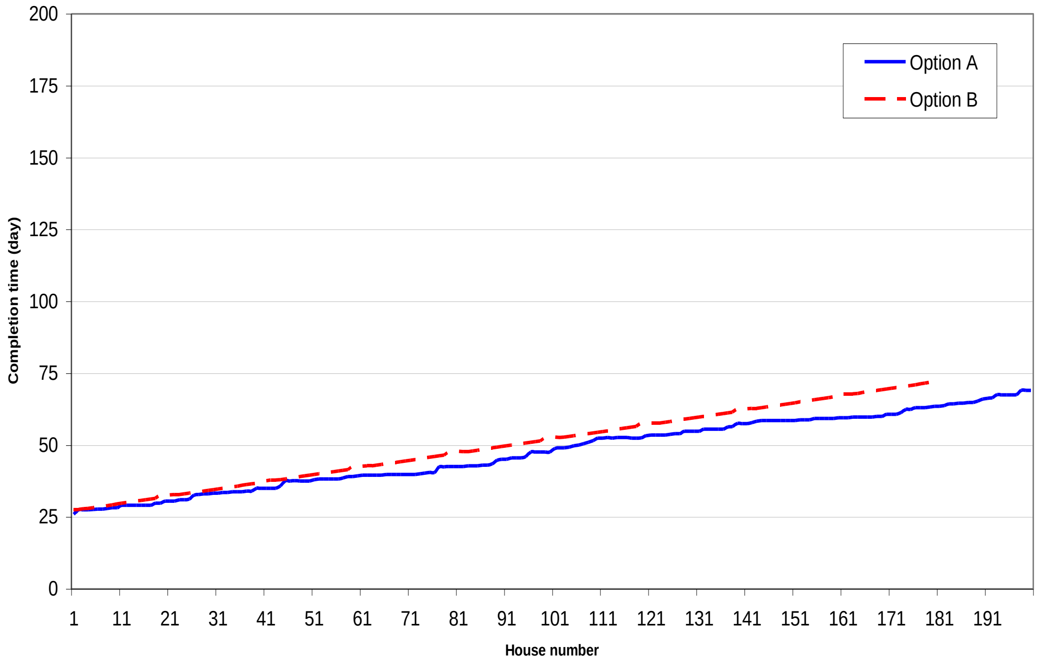


Figure 7-11: Completion time for Options A and B in two-option production

This figure shows that although the completion time for these two options is close, their trend is increasing. For example, house number 100 from Option A takes around 50 days to be built. This house could be completed in 26 days in one-option production.

Further, three, four and five-option production are simulated by adding Option C, D and E to the production process. Figure 7-12 demonstrates the completion time in these production scenarios. As can be clearly seen in this figure, a smooth production line of one-option production (Figure 7-10) became a production line with increasing completion time. This increase results in a considerable cost for the builder and dissatisfaction for customers.

In the extreme case, the five-option production of options A to E shows that a maximum 20 percent variation can lead to a completion time for standard house option A of 200 days. Knowing that this is a house which can be built in 26 days, the disastrous effect of variation can be clearly seen in this case.

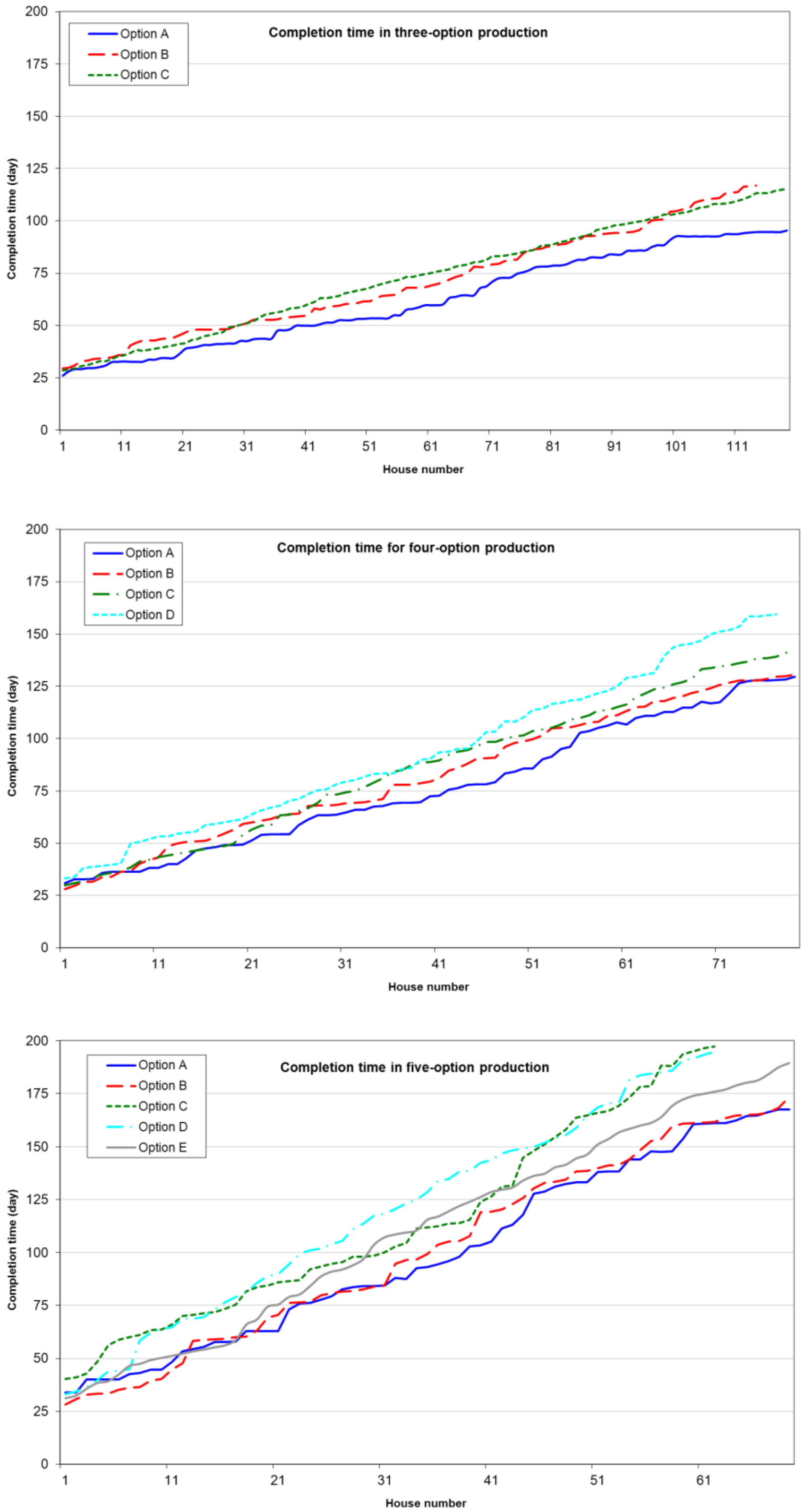


Figure 7-12: Completion time in three, four and five-option production in the first scenario

It was shown that the completion time has an increasing trend in all scenarios. To clarify the effect of variation on completion time, another graph that shows the completion time of the same option in different production strategies is drawn in Figure 7-13.

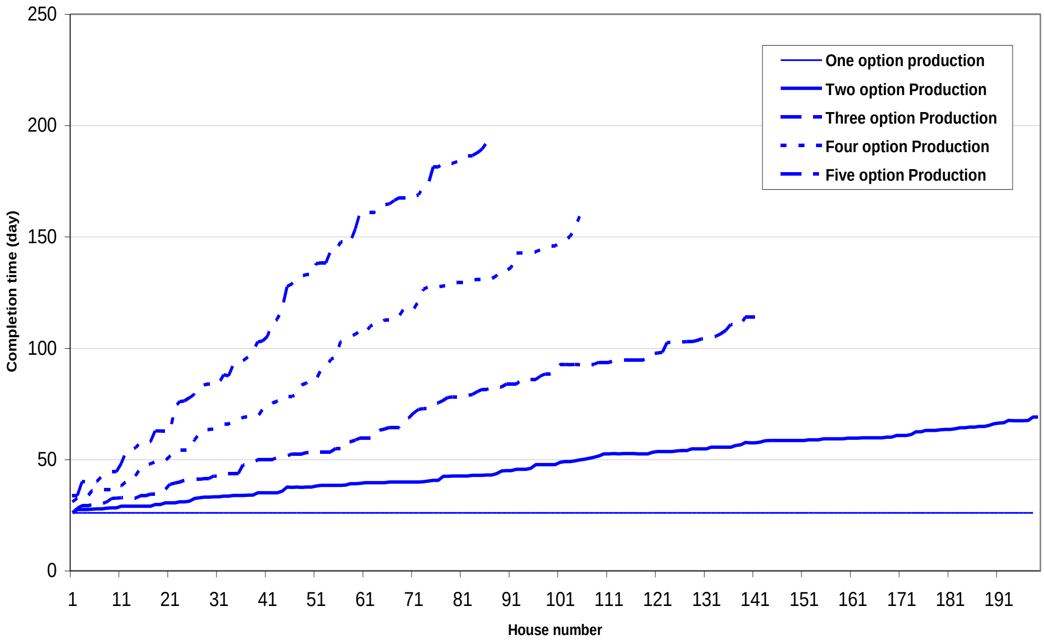


Figure 7-13: Completion time of house Option A in different operation policies

Figure 7-13 also illustrates that five-option production with 20 percent variation has the steepest trend. Twenty percent variation is not considered an unusually large variation in the house building industry. Therefore, the sensitivity of the variability for the industry can be seen in these simulations.

All figures show the completion time increases in all scenarios where larger house option are introduced together with standard house options That means if the new options are larger than the standard option and the system is not revised to absorb the variation, an increasing completion time trend in inevitable.

7.7.3 Introduction of a smaller house option

The previous section explored what would happen to a production building process if the builder decides to introduce a new house option larger than the standard option. In this section, a further scenario is investigated in which the builder introduces a smaller house option with shorter activity durations to decrease the completion time of houses.

Similar to the previous section the starting simulation scenario commences with smooth production. New options are introduced to the production process and the consequences for the completion time reported. The standard house option in this attempt is the biggest option, which is option F. Table 7-3 shows the activity durations for this option and the other options that are later added to the production.

Table 7-3 shows that the activity durations of Options G and H are relatively shorter than for Option F. This is because of the builder's motivation to decrease the completion time using smaller house options. Because the builder's aim is to shorten the completion time, the variation must be relatively large to make a difference for the builder. Thus, 25 percent variation is considered in this part of research.

Table 7-3: Activity durations for different options in the second scenario

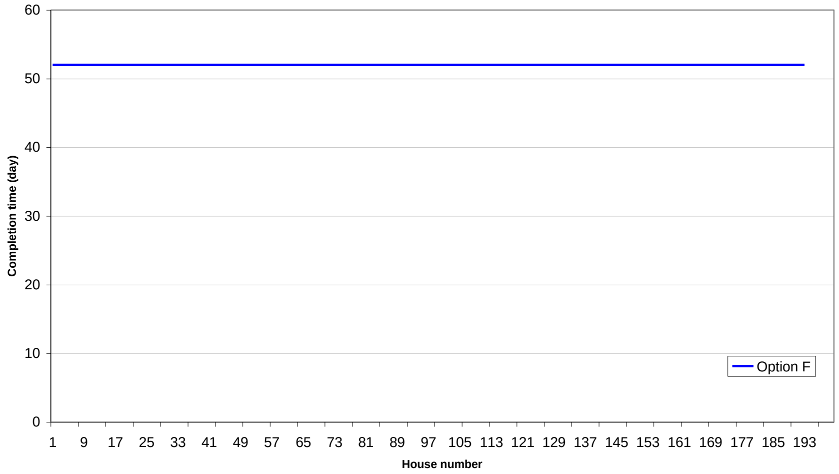
Activity \ Option	F	G	H
Floor Slab	2	1.5	1
Wall Framing	2	1.5	1
Wall Cladding	4	3	2
Electrical Rough In	2	1.5	1
Plumbing Rough In	1	0.75	0.5
Roof Trusses	1	0.75	0.5
Roofing	2	1.5	1
Insulation	1	0.75	0.5
Gyprocking	2	1.5	1
Joint Finishing	4	3	2
Cornicing	2	1.5	1
Sanding	2	1.5	1
2nd Fix Carpentry	4	3	2
Kitchen Fitting	2	1.5	1
Tiling	8	6	4
Painting	10	7.5	5
Electrical Fit Out	1	0.75	0.5
Plumbing Fit Out	1	0.75	0.5
Shower Screen	1	0.75	0.5
Carpeting	1	0.75	0.5
Cleaning	2	1.5	1
Transportation	4	3	2
Commissioning	2	1.5	1

The first graph in the following figure shows the completion time for house Option F in a one-option production. Again, operations produce this option with a constant construction time. This duration is in fact the minimum time needed to build house Option F: 52 days.

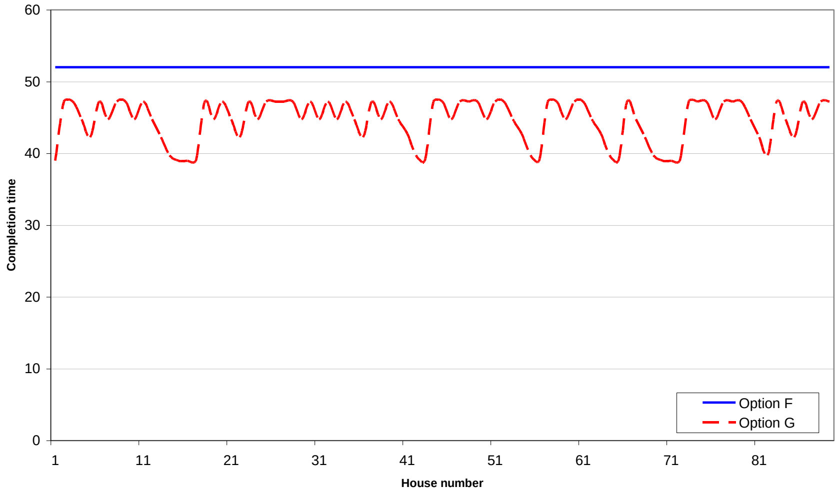
The next situation is when the builder decides to add Option G to the production line. Since the activity durations for Option G are 75 percent of Option F's activity durations, the minimum time needed for Option G is 75 percent of 52 days, which is 39 days. Figure 7-14b shows the actual completion time for Option G. As can be seen in this figure, the completion time has lost its consistency. The completion time is equal to the minimum duration in some occasions; but most often is vacillating between its minimum completion time and Option F completion time.

According to Table 7-3, the minimum completion time for house option H is half of the house option F. Therefore, option H is expected to be built much faster than option F. However, Figure 7-14c shows that this option of house has fluctuating completion times in three-option production. This duration reaches 45 days in some cases, which is against the initial purpose of the builder of reducing construction times.

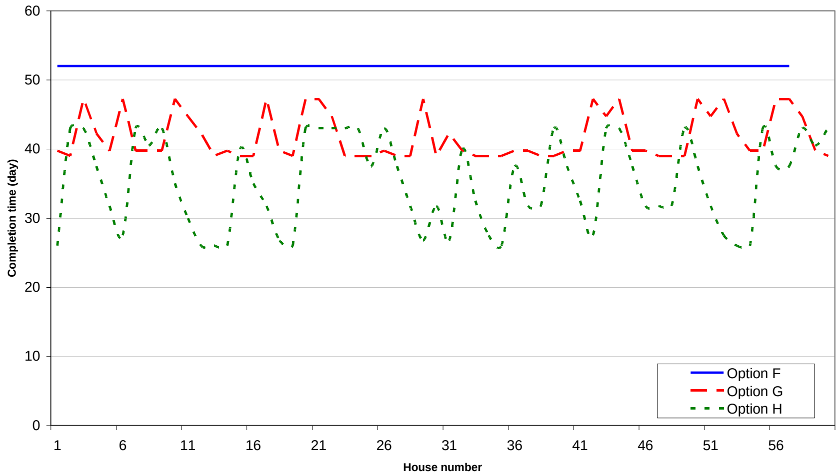
The research demonstrated that the introduction of different house options to a production process result is inconsistent completion time. It was shown than although the completion time of the largest option is still predictable, the time for other options cannot be predicted and it swings between their minimum completion time and the completion time of the largest option.



a) Completion time in one-option production



b) Completion time in two-option production



c) Completion time in three-option production

Figure 7-14: Completion time in one, two and three-option production in the second scenario

Section summary

This part of research investigated the effect of house option variation on the completion time of houses in a production building process. For this purpose, an actual production building process was modelled and different scenarios with house option variation were simulated.

It was argued that one kind of variation is a controllable variation made by the builder. The builder might introduce a smaller option of house than the current options to reach a shorter completion time or the builder might use the variation to attract more customers and offer larger houses than the current ones. For each of these situations the response of the production line is different. This response was monitored through the simulations and demonstrated in different graphs.

It was shown that in a production line with a constant completion time, if larger options were added to the production process, the completion time would grow dramatically. It is therefore, recommended that if larger house options are introduced, then a revised production line for production builders is needed. The production line should be set again with the largest option, otherwise the queue is inevitable and completion times would grow infinitely.

Further, if the new options were mixed with the larger options, the completion time of the new options swings between their own minimum duration and the largest option completion time. This outcome contradicts the initial motivation of the builder to achieve shorter completion times with the introduction of smaller house options. The inconsistency of completion time is a disadvantage to having a mixture of different options in the same production line.

According to this research, the house option variation can have severe consequences for a production builder. It can dramatically increase the completion time of the houses or prevent the builder from achieving the desired completion time. Therefore, to avoid such consequences, it is recommended that any variation in the house options should be considered carefully and the whole production process should be revised accordingly

7.8 Chapter Summary

In this chapter a workflow model was developed based on a production house building process and the specifications and abilities of the model were explained. The house building process used in this chapter included twenty-three activities undertaken by 18 crews and sub-contractors. The model was capable of controlling construction commencements, number of houses under construction and house design options. It also could monitor house completion time, resource utilization and the number of idle houses before each activity.

The chapter continued with the investigation of the effect of workload on the house completion time. It was shown that one way to control the completion time is to control the number of houses under construction. Further, it was demonstrated that workload below the critical number of houses under construction does not affect the completion time; while above this, the completion time has a direct relationship with number of houses under construction.

Then the analyses on the effect of construction commencement intervals on the house completion time were undertaken. The resource utilization, project duration and number of houses under construction were also investigated. It was shown that the commencement intervals should be set according to the slowest activity in the operation. The intervals shorter than this increase the completion time dramatically. In this situation, the number of houses under construction grows substantially which can be disastrous for the house builder. However, the resources reach higher utilization which is desired by the builder.

Analysis of the effect of house design options on the house completion time was the next step. House design option is a controllable variation that is decided by the builder. Therefore, this part of research clarified the consequences of this decision. The investigation was undertaken in two scenarios. In the first scenario, a production builder with a smooth production line decides to add a larger option of house to the production. It was shown for this scenario, house completion time would grow dramatically. Therefore, it was recommended that the production line needs to be revised accordingly.

The second scenario was the situation in which the builder decides to introduce a smaller option to achieve a shorter completion time. It was demonstrated that if the new option is mixed with the larger options, its completion time would vacillate between its own minimum time and the largest option completion time. Therefore, the predictable and shorter completion time, which was the main incentive for the introduction of this house design option, cannot be achieved.

This chapter offers in-depth insight to the house building process. In addition, it suggests that house builders improve their production process and control the house completion time by maintaining control over the number of houses under construction and construction commencement control, and by giving special consideration to house design variation.

8 CHAPTER EIGHT - CONCLUSIONS

8.1 Introduction

Chapter one was an introduction to the research. Chapter two reviewed the current knowledge related to house completion time and Chapter three explained the research design. The analyses were undertaken in four chapters. Chapter four brought up the issue of the recent increase in house completion time and described the validity of different explanation for the changes in this parameter. Then house completion time was analysed in Chapter five using the workflow-based planning approach. The applicability of Little's law to the house building industry was also part of this analysis.

Chapter six focused on implications of the workflow-based planning approach and used average house completion time and number of houses under construction to estimate the house building industry's capacity. Investigation of house completion time at company level was undertaken in Chapter seven through modelling an actual house building process and simulating different operational strategies.

Each chapter addressed one or two objectives of the research and achieved part of the research aim. However, these efforts need to be collected and summarised in a final chapter. Chapter eight is dedicated to this collection and to conclusions.

This chapter starts with the conclusions about objectives and then explains the conclusions for the research aim. Then the implications for theory are described and followed by implications for practice. These included implications for housing policy makers and house builders. The end of this chapter suggests avenues for future research. Therefore, a number of areas for future research are described as the final section for the chapter and for the thesis.

8.2 Conclusions about research objectives

Since the structure of the research was based on the objectives, each chapter investigated a specific objective. Therefore, the summary at the end of each chapter drew the conclusions for that objective. However, to summarise all the conclusions in one chapter, the research objectives which were stated in Chapter three (Section 3.2) are mentioned here as headings, and are followed by their related conclusions.

8.2.1 Objective one

To confirm the potency of workflow-based planning approach and shortcomings of activity-based planning approach in explanation of changes in average house completion time

The first objective of the research was addressed in chapter four. In this chapter, the concern over house completion time was highlighted with its recent increase. This increase was seen in all State case studies and the national case. It was found that the activity-based planning approach and the workflow-based planning approach suggest different reasons for this increase.

The activity-based planning approach relates changes in house completion time to production rate and scope of work. The production rate of the house building industry can be measured by the number of house completions, and therefore, this parameter was used as the proxy for this parameter. Further, average house floor area was adopted as the proxy for the scope of work and the analysis was undertaken using the comparison between the trend of these parameters and average house completion time.

According to the activity-based planning approach, the increase in house completion time may be the result of the loss in production rate. However, New South Wales was the only case study that demonstrated the association between an increase in house completion time and a loss in production rate. In this State, the number of house completions has declined since 2000 and this decline concurred with the increase in house completion time. In the national case of Australia and other States, the increasing trend of average house completion time took place during the time that number of house completions was constant. Therefore, it was concluded that this increase was not associated with the loss in production rate, as is suggested by activity-based planning approach.

The activity-based planning approach suggests that another reason for the increase in house completion time may be the increase in scope of work. Therefore, the trend of average house floor area was also compared with the trend of average house completion time. This comparison showed that the size of houses in some cases grew during the past decade, but without any association with the increase in house completion time. The refuting case in this analysis was South Australia. In this state, the average house completion time decreased during past decade while house completion time increased. This means house builders were building smaller houses over a longer time, which contradicts with the suggestion of the activity-based planning approach.

The workflow-based planning approach focuses on the workflow, and therefore, suggests the level of work in process as the influencing factor on completion time. To investigate this, the number of houses under construction was used as the proxy for the work in process in the house building industry, and the trend was compared with the trend of average house completion time.

As was suggested by workflow-based planning approach, the study demonstrated a strong correlation between number of houses under construction and average house completion time. This correlation was observed in all the State cases and the national case. However, in some instances, the trend of average house completion time did not follow the trend of number of houses under construction. This inconsistency was also explained using the workflow-based planning approach.

According to this planning approach, completion time is influenced by number of houses under construction, as long as the production rate in constant. However, when the production rate changes, this also affects completion time and it must be considered. The analysis on the case studies with some inconsistencies showed that whenever there is an inconsistency between the trend of average house completion time and number of houses under construction, there is a change in the trend of number of house completions.

One example of this phenomenon is the changes in average house completion time in New South Wales during the past decade. In this period, the number of houses under construction decrease, and therefore, house completion time was expected to decrease. However, the actual data showed an increase in house completion time. According to the workflow-based planning approach, in this situation the production rate which is measured by number of house completions is expected to decrease. The actual data of number of house completions demonstrated this decrease and confirmed the workflow-based planning approach suggestion. Other inconsistencies in Queensland and South Australia were also explained using this approach.

The first objective aimed at the confirmation of the shortcomings of the activity-based planning approach and the potentials of the workflow-based planning approach in explanation of changes in house completion time in Australia. This is the justification for the use of the workflow-based planning approach in investigation of house completion time in Australia. The next steps follow this and continue with more detailed analyses using this approach.

8.2.2 Objective two

To investigate the relationship between average house completion time, number of houses under construction and number of house completions

The correlation between average house completion time and number of houses under construction was explored in the previous objective. However, the detail of the correlation and the relationship between these two parameters remained unexplored. This was the second objective of the research and was undertaken in Chapter five. For this purpose, Little's law was used as a hypothesis for the relationship between house completion time, number of houses under construction and number of house completions.

To investigate the applicability of Little's law in the Australian house building industry, the number of houses under construction was predicted using the law and compared with the actual data. The comparison was made using error metrics (MAD, MSE and MAPE), r-square and visual comparisons. Similar to objective one, five State case studies and one national case were investigated. Table 8-1 summarises parts of the results.

Table 8-1: The summary of MAPE and r-square between predicted and actual number of houses under construction for all cases

Case	MAPE	r-square
Australia	4.24%	94%
Victoria	5.23%	93.7%
Western Australia	7.84%	96.7%
South Australia	6.9%	93.8%
New South Wales	10.77%	83%
Queensland	16.56%	86.7%

Table 8-1 shows that Little's law predicts the number of houses under construction in the national case with an error of 4.24%. The r-square is 94%, which also shows a strong relationship between prediction and actual data. The applicability of Little's law in the Australian house building industry was concluded using these comparisons and was presented mathematically as follows:

$$NHUC_{(t)} = AHCT_{(t+2)} * NHC_{(t+2)} \qquad \textit{Equation 8-1}$$

Number *2* in the term *(t+2)* is the lag between the trend of number of houses under construction and average house completion time. This lag was identified for each case study and was explained in chapter five. Since the lag was different for different States, Little's law outcomes were different, and therefore, the law was articulated separately in Chapter five. However, the applicability of the law was shown in all the case studies.

The two case studies that had the highest errors were New South Wales and Queensland. Number of houses under construction in New South Wales was underestimated by the law. This was explained by the law with the extra capacity flowing into the state from other states. This is due to geography of the State where the northern area of the State is closer to population centre in Queensland than the population centres in the state.

The number of houses under construction in Queensland was predicted by Little's law with an overestimation. This was explained by the law with the flow of capacity out of the state, which complied with the findings in New South Wales. These two cases demonstrated that the inconsistencies in Table 8-1 can also be explained by the law, and therefore, strengthened the argument for Little's law applicability in the Australian house building industry.

Further, the workflow-based planning approach suggests a two-phase relationship between cycle time and work in process. According to this, cycle time remains at its minimum level as long as work in process is under the critical level, and it increases by the increase of work in process over its critical level. This suggestion was interpreted for the house building industry and the two-phase relationship between average house completion time and number of houses under construction was hypothesised.

This relationship was investigated and it was demonstrated in Chapter five that a two-phase relationship exists between average house completion time and number of houses under construction in five case studies. The only case in which two-phase relationship was not observed was New South Wales. It was explained that this state built its house building capacity in the late 1980s when there were more than 22,500 houses under construction and has never reached that level again. Therefore, the industry has worked under the capacity since then and the data merely showed the first phase of the relationship.

The other four State case studies and the national case showed a clear pattern in the relationship of average house completion time and number of houses under construction. In this pattern, average house completion time stays within a specific range when the number of houses under construction is under a particular level. The growth in number of houses under construction over this level causes average house completion time to extend relatively.

The applicability of Little's law and the validity of the two-phase relationship demonstrated that the Australian house building industry works like a production operation, and therefore, the workflow-based planning can predict and explain its dynamics.

The next objective focuses on implications of the workflow-based planning approach in the house building industry, and introduces the average house completion time as an indicator of the house building industry capacity.

8.2.3 Objective three

To explore the implications of the relationship between average house completion time and number of houses under construction; and the introduction of average house completion time as an indicator of industry's capacity

Chapter five showed that there is a two-phase relationship between average house completion time and number of houses under construction. These two phases are connected with a turning point which is called critical number of houses under construction. It was argued in Chapter six that the critical number of houses under construction is the maximum workflow that the house building industry can work on without increasing the completion time. At the critical number of houses under construction, the throughput of the industry is also at the maximum level, and therefore, its estimation became one objective of the research.

The two-phase relationship was explained in the previous objective. The critical number of houses under construction is located at the turning point between the two phases. Thus, the trend line for each phase was drawn and their intersection was calculated. This intersection was considered as the critical number of houses under construction, or the house building industry's capacity. Table 8-2 summarises the result of the analysis and reports the house building industry's capacity in four States and the whole country.

Table 8-2: Critical number of houses under construction for Australia and different states

Case study	Estimated $NHUC_0$
Australia	48,000
Victoria	10,700
Western Australia	5,300
South Australia	3,200
Queensland	7,200

As was explained earlier, critical number of houses under construction is the capacity of the industry. This is the level at which the industry has enough resources to work with. The workflow over this level means some parts of the workflow have to sit idle waiting for resources and this causes their completion time to increase.

Therefore, to examine the validity of these estimations in different States and at the national level, the historical data of average house completion time and number of houses under construction were drawn in a graph, along with the estimated critical number of houses under construction, and minimum average house completion time. According to the workflow-based planning approach, if the historical data showed that in a particular time the number of houses under construction was over the estimated critical levels, the house completion time was expected to be longer than the minimum level. Further, if the number of houses under construction was under the critical level, house completion time was expected to be around the minimum level.

These dynamics were observed in all cases and the validity of the estimations was proven. For example, in the national case of Australia, it was shown that whenever the number of houses under construction was more than 48,000 houses, house completion time grew over the minimum level, and whenever the industry worked under this level, house completion time stayed at the minimum level.

These analyses, and the explanation of industry's dynamics using estimated critical number of houses under construction and the minimum house completion time were undertaken in Chapter six. These explanations are separated for each State and the whole country, and therefore, they can be used separately for the readers who are interested in a specific State.

So far, house completion time at industry level was discussed. The dynamics of the house building industry were explained and the industry's capacity was estimated. However, house completion time cannot be improved without consideration of the house building process at company level. Therefore, the next two objectives focus on the operational strategies at the company level and highlight the operation factors affecting house completion time

8.2.4 Objective four

To establish a workflow planning model that describes the house building process at company level

The investigation of house completion time needed a workflow model of a house building process. Therefore, an actual production building process was used as a case study and was modelled. The house building process included twenty-three activities undertaken by eighteen crews and sub-contractors.

The details of the process and the related data were collected through site observations, interview with sub-contractors and crews, interview with site manager and documents analysis. The documents included the sub-contractors invoices and material orders. The data used for the modelling consisted of most often time needed for activity completions, the logic and relationship between activities, list of sub-contractors and crews, general schedule of one house construction, material needed for activities, and idle time in the process.

The model was developed using a general purpose simulation software called Simul8. This was a discrete event simulator and was capable of programming in case it was needed. The model consisted of different constructs, components and specifications. They included the generation of a set of work items, computation of the number of work items at any downstream steps, work in process controller, computation of number of work items waiting for the resources, completion time calculator, activity work centres, and resources. This model was developed for the further investigation of different operational strategies affecting house completion time. Hence, many of the strategies were implemented in the model using programming.

Note that, although the case study was a production building process, the construction methods, techniques and sequences were similar to on-site construction. Therefore, the result of this study is also applicable for on-site construction practitioners.

8.2.5 Objective five

To explore the implications of workflow planning in finding the effect of commencement intervals and house design variation on completion time

There are many aspects to the implications of the workflow-based planning approach in the house building process. However, this study focused on the operational strategies controlling the beginning of the process and their effects on completion time. These strategies were: control on number of houses under construction, construction commencement interval decisions, and the existence of different house design options in the process.

The research showed that when the number of houses under construction is constant, the completion time is constant and therefore, predictable. This suggests the house builder should place a control at the beginning of the process and limit the number of houses under construction, instead of having many controls through the whole process. The result of such controls is a smooth production line without wasting too much energy and effort in controlling each activity.

Further, it was shown that a continuous house building process has a critical number of houses under construction. The house completion time remains at the minimum level when the workflow is under the critical level and it increases when the workflow goes above this level.

Construction commencement intervals decision and its effect on house completion time, as well as other operational parameters were also investigated in the research. It was explained that the importance of construction the commencement decision is usually ignored by house builders. This decision is normally made based on the existence of an order and the availability of the related crew for the first activity. There is also a perception that to increase resource utilization and to decrease the project duration, the jobs must start as soon as possible. However, this perception has its effects on house completion time and other operational parameters.

To highlight the importance of construction commencement intervals, different construction commencement intervals were simulated and their consequences on house completion time and some other operational parameters were collected and compared.

It was shown that the commencement intervals should be set according to the slowest activity in the operation. Intervals shorter than this increase the completion time dramatically. In this situation, the number of houses under construction grows substantially which can be disastrous for the house builder.

It was also demonstrated that a shorter interval can increase the utilization of the resources but that this utilization has a limitation and in many cases, the resources do not reach 100 percent utilization. In fact, there is a maximum possible utilization for all resources. This maximum utilization can be a decision making point for outsourcing.

Analysis of the effect of house design options on house completion time was the next step. Number of house design options is a controllable variation that is decided by the builder. Therefore, this part of research clarified the consequences of this decision. The investigation was undertaken in two scenarios. In the first scenario, a production builder with a smooth production line decides to add a larger option of house to the production. It was shown that in this scenario, house completion time would grow dramatically. Therefore, it was recommended that the production line needs to be revised accordingly.

The second scenario was the situation in which the builder decides to introduce a smaller option to reach shorter completion time. It was demonstrated that if the new option is mixed with the larger options, its completion time would vacillate between its own minimum time and the largest option completion time. Therefore, the predictable and shorter completion time, which was the main incentive for the introduction of this house design option, cannot be achieved.

8.3 Conclusions about research aim

The research aim was: "***The investigation of house completion time in Australia using workflow-based planning approach***".

The investigation started by reviewing the current knowledge around house completion time. The review of housing literature showed that although house completion time is a parameter related to the housing area, it was not adequately discussed in this area. However, construction management literature extensively researched completion time and its influencing factors by developing construction planning methods.

It was explained in Chapter two that these planning methods can be classified into two approaches, namely activity-based planning and workflow-based planning. These approaches were further used for the explanation of changes in house completion time in Australia.

Activity-based planning approach suggested the industry production rate and scope of work as parameters affecting house completion time. Number of house completions and average house floor area were adopted as proxies for these parameters and their effect on house completion time was investigated. It was shown in Chapter four that while house completion time increased in Australia, no loss of production rate and no significant increase in scope of work occurred.

Thus, the suggestion by the activity-based planning approach could not adequately explain the changes in house completion time.

Number of houses under construction is a parameter suggested by the workflow-based planning approach as an influencing factor on house completion time. This parameter was investigated through the comparison between its trend and the trend of average house completion time. It was demonstrated that the changes in the Australian average house completion time were strongly correlated with the changes in number of houses under construction. Thus, the suggestion by the workflow-based planning approach held true. This showed the potentials of this approach for explanation of house building industry dynamics in Australia and hence it was the approach taken for further investigation.

Since the correlation between average house completion time, number of house completions and number of houses under construction was investigated, the next step was to explore their possible relationship. This relationship was also suggested by the workflow-based planning approach and was an adoption of Little's law from production planning. Little's law explains the relationship between cycle time, work in process, and throughput; and was used as a suggestion for relationship between the abovementioned three parameters. This suggestion was examined through comparison between predicted number of houses under construction using Little's law and the actual data. The result showed the applicability of Little's law in the Australian house building industry and the following equation was concluded.

$$NHUC_t = AHCT_{(t+l)} * NHC_{(t+l)} \qquad \textit{Equation 8-2}$$

In this equation, *t* is time and *l* is the lag between the trend of average house completion time and number of houses under construction. This lag was estimated for Australian house building industry and the State industries.

A two-phase relationship between average house completion time and number of houses under construction was another issue investigated in the research. This importance of this relationship was important because it helps in finding the industry's capacity. It was shown that there is a two-phase relationship between these two parameters in the Australian house building industry. The turning point between these two phases indicated the industry's capacity. According to this analysis, the Australian house building industry capacity is 48,000 houses. This shows that the industry can work on this many houses with minimum completion time. The State industry capacities were also estimated in the research.

The investigation of house completion time could not be finished without addressing the issues in the house building process at company level. Thus, an actual house building process was modelled and different operational strategies were simulated. These strategies were focused on the implementation of some controls on the beginning of the construction process. These were the control on workflow or number of houses under construction, control on construction commencement intervals, and control on house design options in the process.

It was shown that having a constant number of houses under construction returns constant completion time and a smooth production. It was demonstrated that the construction commencement intervals should be decided according to the slowest activity. Pushing the system by intervals shorter than the slowest activity, increases completion time by adding idle time to the process.

Offering different design options to the customers is a normal practice among Australian house builders. It was shown that if a builder with a smooth production line decides to add a new house design which is larger than the current designs without revising the production, the completion time of all house options grows dramatically. Further, if this builder decides to add a new house design smaller than current options in order to achieve shorter completion times, the completion time of the new option fluctuates between its minimum completion time and the completion time of the largest option.

8.4 Implications for theory

The analysis started with the comparison between the activity-based planning approach and the workflow-based planning approach. These are the planning theories, which have been applied in construction projects for a long time. This research showed that the activity-based planning approach falls short in explanation of house building industry dynamics. On the other hand, the workflow-based planning approach demonstrated a significant potential for understanding the industry.

One principle used in the operation management and production planning is Little’s law. Little’s law explain the relationship between work in progress, cycle time and throughput of the system. The use of production planning in construction projects is a recent trend. However, in the housing sector and between housing experts, this is a new idea. This research showed that Little’s law is applicable for the analysis of house building industry dynamics and this can be a platform for further understanding of this industry.

In house building industry, cycle time of products, which is house completion time, is long, and therefore, the workflow changes during this time. Further, a lag between the trend of house completion time and number of houses under construction was observed in all case studies. Therefore, a time factor was added to Little's law to make it suitable for house building industry.

At company level, this research demonstrated that workflow planning can be a justified replacement for the current methods of planning which are more focused on activities. Using workflow planning approach, the idle time in the process can be seen and the effect of capacity limitation can be clarified. The idle time in the housing projects is an important factor because of the volume of investment. This idle time affects the capital cost of the project and consequently increases the final price of the houses and severely impact affordability.

8.5 Implications for practice

The outcomes of this research can be implemented at State and national level by housing experts and policy makers and at company level by house builders. Following sections describe these outcomes.

Implications for housing analysts and housing policy makers

- Although house completion time is a parameter related to housing and it has a significant impact on housing supply and housing affordability, it is not adequately discussed by housing experts. This research called attention to the recent increase of house completion time in Australia and highlighted the importance of study on this parameter.

- Workflow-based planning is an approach implemented in construction projects. This approach also has potentials in explanation of house building industry dynamics. Parts of these potentials were demonstrated in this research.

- The research showed that the Australian house building industry works like a production system. Therefore, production planning methods and techniques can be adopted and used in the analysis of the industry and for policy making toward its improvement.

- Little's law (explaining the relationship between average house completion time, number of house completions and number of houses under construction) is applicable for this industry. This law is a platform for decreasing waste and increasing productivity in manufacturing. Therefore, it can be used for the same purposes in the house building industry.

- The capacity limitations of the industry were emphasised and estimated for different States and the whole country. These estimations can be used as benchmarks for assessment of the effectiveness of policies in the industry outputs.

- The estimated minimum average house completion time can be used as an indicator of shortage in housing supply. When the actual average house completion time goes over this minimum level, this points to the lack of capacity in the industry for building more houses, and consequently shortage of supply occurs.

Implications for house builders

- The indirect control of house completion time can be achieved through control of workflow. Constant number of houses under construction produces a return in constant completion time and a smooth production line.

- Pushing house building production which means having more jobs in order to increase resource utilization and reduce duration of housing projects can lead to a dramatic increase in house completion time and number of houses under construction. Further, each resource has a maximum utilization which is not affected by commencement intervals.

- In a house production with a constant completion time, if larger options are added to the production process, the completion time would grow dramatically. It is therefore, recommended that an introduction of larger house types needs a revised production line for house builders. The production should be set again with the largest type, otherwise queuing is inevitable and completion times would grow infinitely.

- Further, if the new options added to current smooth production process are mixed with the larger types, the completion time of the new options would swing between their own minimum duration and the largest type completion time. This outcome contradicts the motivation of the builder to achieve shorter completion times with the introduction of smaller house types. The inconsistency of completion time is a disadvantage to having a mixture of different types in the same production line.

- According to this research, house option variations can have severe consequences for a house builder. It can dramatically increase the completion time of the houses or prevent the builder from achieving the desired construction duration. Therefore, to avoid such consequences, it is recommended that any variation in house option should be considered carefully, and the whole production process should be revised accordingly.

8.6 Implications for future research

This research was the first attempt to applying the workflow-based planning approach in analysis of house building industry in Australia. It clarified the potentials in this approach and the researcher hopes the research will be used as platform for further analysis. Some of the areas that can be investigated in the future are described as follows.

- This research was undertaken in Australian context. However, the principles used are universal and may be applicable in other countries and other contexts. In this regard, countries with natural boundaries and with limited resource movement can be proper cases. The UK and New Zealand are two countries with this specifications and can be investigated with this research approach.

- This research investigated the possible effects on house completion time of three factors: industry's production rate; average size of houses; and number of houses under construction. However, there are other parameters whose influence on completion time can be further investigated. Occupation health and safety regulations and climate change are two examples of parameters affecting house completion time.

- It was shown that the Australian house building industry works similar to production systems. Thus, applicability of production planning knowledge in this industry is a possibility which can be further investigated. One result of this research is the indication of house building capacity constraint, in Australia. This result can be extended by finding effective ways of increasing capacity. These include the effect of number of skilled workers in the industry, the level of skills among sub-contractors, sub-contracting systems, and industry structure. The study showed that the capacity of the Australian house building industry has not increased sufficiently during last twenty years. However, many changes happened in the industry in an attempt to increase the output of the industry. Research aiming to reveal the reasons for the limited effectiveness of these changes can be a significant contribution to house building industry by future researchers.

- This research showed a high level of workflow in house building industry. In production planning, high level of workflow leads to less productivity and efficiency. However, this needs to be further investigated in the house building industry.

- Although the recent trend in Australian house building industry is toward volume house building, the benefits of having continuous production are not fully recognized and needs further investigation.

This thesis is an attempt in introduction of workflow planning approach to the Australian house building industry. In this attempt, the crucial factors in the industry such as house completion time, number of houses under construction, industry’s house building capacity, the applicability of Little’s law in the industry, the impacts of construction commencement intervals and having different design options on the house building process were investigated. The researcher hopes this thesis triggers further attempts in the analysis of the industry’s dynamics using workflow planning approach and introduces this approach to industry’s practitioners.

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APPENDIX A - ACTUAL DATA

- Average house completion time (AHCT)
- Number of houses under construction (NHUC)
- Number of house completions (NHC)
- Average house floor area

Australia:

	NHUC	AHCT	NHC
1987.1	43,297	1.953	20,344
1987.2	42,968	1.903	22,102
1987.3	44,531	1.894	21,867
1987.4	46,179	1.887	24,699
1988.1	50,381	1.896	20,982
1988.2	54,081	1.980	25,204
1988.3	61,755	1.845	26,295
1988.4	63,534	1.895	33,080
1989.1	68,662	2.022	25,271
1989.2	70,041	2.063	30,921
1989.3	65,831	2.083	31,768
1989.4	57,114	2.122	33,575
1990.1	53,747	2.143	26,286
1990.2	51,914	2.050	26,235
1990.3	50,067	2.058	25,011
1990.4	45,789	1.969	27,663
1991.1	44,743	1.883	21,615
1991.2	43,679	1.955	23,520
1991.3	45,101	1.786	23,956
1991.4	45,193	1.698	26,846
1992.1	44,606	1.783	23,557
1992.2	46,982	1.736	25,495
1992.3	49,184	1.609	26,781
1992.4	47,412	1.677	32,192
1993.1	47,178	1.719	26,882
1993.2	48,086	1.649	29,397
1993.3	50,110	1.586	30,497
1993.4	47,283	1.636	34,325
1994.1	48,295	1.724	27,481
1994.2	51,681	1.608	29,940
1994.3	54,313	1.656	30,999
1994.4	49,928	1.645	36,044
1995.1	46,188	1.737	27,660
1995.2	43,129	1.802	27,303
1995.3	40,471	1.723	26,289
1995.4	36,014	1.706	26,589
1996.1	34,198	1.788	20,677
1996.2	33,734	1.711	21,255
1996.3	34,110	1.704	20,261
1996.4	33,131	1.622	22,688
1997.1	34,501	1.752	18,982
1997.2	35,648	1.612	21,794
1997.3	37,075	1.649	22,331
1997.4	37,524	1.592	26,143

	NHUC	AHCT	NHC
1998.1	40,110	1.660	21,154
1998.2	41,140	1.698	25,131
1998.3	42,497	1.727	25,813
1998.4	41,354	1.660	26,516
1999.1	42,563	1.769	21,382
1999.2	44,225	1.804	25,634
1999.3	47,814	1.734	24,696
1999.4	49,321	1.790	28,452
2000.1	55,474	1.806	25,474
2000.2	52,214	1.789	33,028
2000.3	44,273	1.901	26,781
2000.4	37,770	2.008	25,462
2001.1	34,793	2.058	19,572
2001.2	34,550	1.972	20,560
2001.3	40,829	1.792	20,954
2001.4	45,282	1.683	25,213
2002.1	49,746	1.794	22,415
2002.2	51,707	1.789	27,605
2002.3	57,633	1.865	25,915
2002.4	54,796	1.899	31,248
2003.1	54,837	1.929	26,017
2003.2	53,633	2.064	26,456
2003.3	57,667	1.973	26,655
2003.4	59,864	2.015	29,136
2004.1	63,149	2.088	24,187
2004.2	63,059	2.181	28,749
2004.3	62,622	2.236	28,915
2004.4	63,320	2.250	26,778
2005.1	62,548	2.239	23,592
2005.2	61,826	2.392	27,078
2005.3	61,677	2.258	28,087
2005.4	58,077	2.275	29,495
2006.1	59,304	2.266	21,715
2006.2	60,624	2.318	24,737
2006.3	66,151	2.207	23,359
2006.4	65,738	2.334	27,514
2007.1	65,104	2.402	24,466
2007.2	63,271	2.428	27,447
2007.3	65,127	2.378	25,580
2007.4	65,389	2.364	27,924
2008.1	67,642	2.432	21,574
2008.2	68,774	2.438	25,813
2008.3	68,460	2.448	25,577
2008.4	61,808	2.445	29,886

Victoria:

	NHUC	AHCT	NHC
1987.1	16,095	2.366	6,381
1987.2	16,170	2.121	6,745
1987.3	15,327	2.388	6,938
1987.4	14,934	2.286	7,590
1988.1	16,120	2.151	5,506
1988.2	15,784	2.222	7,639
1988.3	17,022	1.966	7,037
1988.4	17,793	2.111	8,349
1989.1	19,056	2.140	6,861
1989.2	20,159	2.146	8,289
1989.3	19,623	2.157	8,062
1989.4	17,437	2.274	9,276
1990.1	17,319	2.297	6,515
1990.2	15,816	2.179	7,895
1990.3	14,896	2.381	6,930
1990.4	12,580	2.201	7,768
1991.1	12,281	2.232	4,915
1991.2	11,512	2.222	5,602
1991.3	11,795	2.053	5,044
1991.4	11,597	1.954	6,080
1992.1	11,206	2.246	5,101
1992.2	11,210	2.013	6,176
1992.3	11,409	1.786	5,964
1992.4	11,896	1.807	6,432
1993.1	11,596	1.881	6,153
1993.2	11,772	1.742	6,550
1993.3	11,188	1.841	7,308
1993.4	11,696	1.615	6,897
1994.1	12,331	1.734	5,988
1994.2	12,362	1.777	6,925
1994.3	12,477	1.791	6,984
1994.4	11,931	1.781	8,006
1995.1	11,080	1.807	6,311
1995.2	10,668	2.006	6,079
1995.3	10,190	1.704	6,267
1995.4	8,620	1.756	6,640
1996.1	8,392	1.942	4,582
1996.2	8,066	1.859	4,394
1996.3	8,623	1.838	3,848
1996.4	7,624	1.964	5,081
1997.1	8,176	1.995	3,997
1997.2	8,937	1.708	4,687
1997.3	9,537	1.720	5,102
1997.4	10,720	1.691	5,842

	NHUC	AHCT	NHC
1998.1	11,512	1.767	5,242
1998.2	12,368	1.844	6,239
1998.3	12,740	1.904	6,951
1998.4	13,127	1.842	6,995
1999.1	13,846	1.910	5,699
1999.2	14,455	2.023	7,281
1999.3	15,667	1.921	6,939
1999.4	15,741	1.975	8,719
2000.1	18,128	2.075	6,569
2000.2	17,861	2.045	9,004
2000.3	15,779	2.102	8,224
2000.4	13,810	2.080	7,826
2001.1	13,146	2.310	6,132
2001.2	13,028	2.339	6,697
2001.3	14,582	2.102	6,700
2001.4	16,113	2.015	7,173
2002.1	17,541	2.039	6,755
2002.2	18,854	1.902	8,049
2002.3	19,778	2.158	8,298
2002.4	18,528	2.152	9,733
2003.1	18,850	2.129	7,470
2003.2	17,001	2.285	8,666
2003.3	18,640	2.160	7,677
2003.4	18,848	2.283	8,526
2004.1	19,495	2.247	7,016
2004.2	20,007	2.384	8,275
2004.3	18,974	2.520	8,816
2004.4	19,214	2.438	7,639
2005.1	18,526	2.252	6,834
2005.2	19,359	2.674	7,044
2005.3	18,099	2.255	9,081
2005.4	16,888	2.413	8,429
2006.1	17,116	2.395	6,301
2006.2	17,925	2.214	6,622
2006.3	19,886	2.206	6,491
2006.4	19,338	2.345	7,813
2007.1	17,840	2.588	7,441
2007.2	18,017	2.555	7,122
2007.3	18,225	2.376	7,816
2007.4	19,002	2.303	7,493
2008.1	19,527	2.660	5,814
2008.2	20,521	2.433	7,098
2008.3	21,581	2.606	7,300
2008.4	20,168	2.474	9,074

New South Wales:

	NHUC	AHCT	NHC
1987.1	11,565	1.993	4,774
1987.2	11,932	2.132	4,915
1987.3	13,143	1.933	4,827
1987.4	14,809	1.998	5,591
1988.1	16,466	2.078	5,406
1988.2	17,430	2.263	6,484
1988.3	19,988	2.233	6,875
1988.4	20,226	2.191	8,763
1989.1	22,347	2.256	6,284
1989.2	20,987	2.298	8,595
1989.3	19,858	2.368	8,451
1989.4	17,535	2.399	8,251
1990.1	17,304	2.382	6,289
1990.2	17,707	2.302	6,174
1990.3	17,042	2.465	6,123
1990.4	16,114	2.322	7,153
1991.1	16,186	2.053	5,753
1991.2	14,959	2.351	6,476
1991.3	15,621	2.175	5,959
1991.4	15,751	2.005	6,718
1992.1	15,482	1.974	5,958
1992.2	15,764	2.010	6,619
1992.3	15,777	1.813	6,812
1992.4	15,235	2.021	7,513
1993.1	14,895	1.960	6,438
1993.2	15,326	1.904	6,419
1993.3	16,094	1.659	6,884
1993.4	14,497	1.869	8,479
1994.1	13,807	2.000	6,847
1994.2	15,727	1.719	6,420
1994.3	16,185	1.825	7,666
1994.4	15,158	1.763	8,561
1995.1	14,853	1.979	6,241
1995.2	14,214	1.982	6,826
1995.3	13,087	1.938	7,181
1995.4	11,922	1.892	6,790
1996.1	11,374	2.041	5,931
1996.2	10,961	1.869	6,140
1996.3	10,607	1.805	5,995
1996.4	10,643	1.686	6,048
1997.1	10,878	1.903	5,565
1997.2	10,788	1.847	5,853
1997.3	11,300	1.775	5,714
1997.4	11,298	1.699	7,082

	NHUC	AHCT	NHC
1998.1	12,130	1.706	5,631
1998.2	11,991	1.842	6,958
1998.3	12,667	1.809	6,536
1998.4	11,589	1.749	7,288
1999.1	12,647	1.890	5,425
1999.2	12,708	1.828	7,069
1999.3	13,792	1.842	6,122
1999.4	13,658	1.959	7,416
2000.1	15,224	1.874	6,757
2000.2	14,753	1.862	8,256
2000.3	11,981	1.963	7,157
2000.4	9,824	2.142	6,753
2001.1	9,397	2.274	4,420
2001.2	9,119	1.963	4,761
2001.3	10,208	1.876	4,643
2001.4	11,509	1.825	5,812
2002.1	12,434	1.972	5,079
2002.2	12,855	1.935	6,046
2002.3	14,477	1.899	5,176
2002.4	13,251	1.935	7,576
2003.1	12,922	2.045	5,637
2003.2	13,117	2.161	5,282
2003.3	13,451	2.094	5,430
2003.4	13,584	2.198	6,095
2004.1	14,119	2.340	4,770
2004.2	13,525	2.313	6,026
2004.3	13,454	2.180	5,766
2004.4	13,477	2.286	5,560
2005.1	12,721	2.328	4,720
2005.2	12,445	2.468	4,696
2005.3	11,280	2.603	5,440
2005.4	10,134	2.343	5,434
2006.1	10,228	2.340	3,428
2006.2	9,922	2.413	3,959
2006.3	10,490	2.254	3,684
2006.4	10,597	2.348	4,059
2007.1	10,663	2.296	3,733
2007.2	9,985	2.323	3,837
2007.3	10,274	2.340	3,485
2007.4	10,417	2.578	3,676
2008.1	11,261	2.451	3,128
2008.2	11,717	2.367	3,391
2008.3	11,541	2.383	3,622
2008.4	10,259	2.603	4,209

Queensland:

	NHUC	AHCT	NHC
1987.1	4,561	1.387	3,641
1987.2	4,183	1.352	4,404
1987.3	4,825	1.243	4,410
1987.4	5,616	1.326	5,036
1988.1	6,163	1.519	4,806
1988.2	7,941	1.372	5,154
1988.3	8,905	1.371	6,720
1988.4	9,017	1.407	8,383
1989.1	9,139	1.652	6,257
1989.2	10,021	1.559	6,839
1989.3	8,618	1.591	7,597
1989.4	7,886	1.491	7,417
1990.1	6,184	1.538	6,607
1990.2	6,572	1.481	5,432
1990.3	6,428	1.373	5,987
1990.4	6,102	1.301	6,295
1991.1	5,880	1.430	5,199
1991.2	7,079	1.332	5,506
1991.3	7,073	1.293	6,881
1991.4	7,533	1.201	7,446
1992.1	7,364	1.329	6,630
1992.2	8,822	1.266	6,148
1992.3	9,746	1.274	7,543
1992.4	8,617	1.378	10,005
1993.1	8,475	1.427	7,545
1993.2	8,559	1.349	8,507
1993.3	9,133	1.321	8,756
1993.4	7,733	1.470	10,539
1994.1	8,230	1.469	7,545
1994.2	9,504	1.217	7,953
1994.3	10,521	1.329	8,669
1994.4	9,118	1.335	10,190
1995.1	7,652	1.349	7,720
1995.2	6,971	1.442	6,948
1995.3	6,820	1.409	6,253
1995.4	5,962	1.310	6,854
1996.1	5,759	1.387	4,992
1996.2	6,049	1.256	5,753
1996.3	6,216	1.383	5,524
1996.4	6,148	1.258	6,349
1997.1	6,137	1.391	4,988
1997.2	6,284	1.267	5,690
1997.3	6,486	1.349	5,908
1997.4	6,116	1.282	6,610

	NHUC	AHCT	NHC
1998.1	6,497	1.369	5,058
1998.2	6,625	1.334	5,797
1998.3	5,767	1.480	6,225
1998.4	5,198	1.284	5,709
1999.1	5,271	1.288	4,045
1999.2	5,970	1.367	4,793
1999.3	5,750	1.341	5,643
1999.4	6,640	1.249	5,454
2000.1	7,279	1.390	5,298
2000.2	6,004	1.360	7,762
2000.3	4,109	1.422	5,282
2000.4	3,750	1.316	3,907
2001.1	3,513	1.328	3,404
2001.2	4,136	1.216	3,770
2001.3	6,143	1.230	4,546
2001.4	6,397	1.217	6,093
2002.1	7,511	1.315	4,982
2002.2	7,575	1.433	6,534
2002.3	8,727	1.460	6,474
2002.4	9,003	1.460	6,436
2003.1	8,055	1.547	6,692
2003.2	8,603	1.597	5,469
2003.3	9,551	1.555	6,807
2003.4	10,501	1.396	7,198
2004.1	11,557	1.676	5,719
2004.2	11,654	1.726	6,914
2004.3	11,651	1.809	7,262
2004.4	11,012	1.873	6,798
2005.1	10,659	1.899	5,960
2005.2	9,353	1.812	7,538
2005.3	10,172	1.736	6,419
2005.4	9,107	1.592	7,091
2006.1	9,243	1.700	4,883
2006.2	9,863	1.778	5,750
2006.3	11,915	1.653	5,277
2006.4	11,831	1.874	7,009
2007.1	12,449	1.810	5,905
2007.2	12,334	1.904	7,465
2007.3	14,133	1.913	6,084
2007.4	14,443	1.903	8,249
2008.1	15,073	2.001	5,720
2008.2	14,812	2.121	7,198
2008.3	13,900	2.103	7,373
2008.4	10,979	2.011	8,268

Western Australia:

	NHUC	AHCT	NHC
1987.1	4,847	1.749	3,097
1987.2	4,673	1.639	3,132
1987.3	5,133	1.649	3,024
1987.4	4,727	1.661	3,659
1988.1	5,223	1.628	2,953
1988.2	6,748	1.696	2,756
1988.3	9,086	1.784	2,928
1988.4	9,619	1.897	4,311
1989.1	11,117	2.102	3,251
1989.2	11,686	2.273	4,170
1989.3	10,277	2.339	4,585
1989.4	7,407	2.322	5,311
1990.1	6,222	2.525	4,248
1990.2	5,240	2.107	3,544
1990.3	4,989	2.000	2,989
1990.4	4,605	1.999	2,974
1991.1	4,147	1.791	2,738
1991.2	4,115	1.858	2,684
1991.3	4,670	1.800	2,570
1991.4	4,234	1.712	3,257
1992.1	4,251	1.675	2,779
1992.2	4,795	1.649	2,933
1992.3	5,516	1.589	2,942
1992.4	5,197	1.584	4,011
1993.1	5,630	1.558	3,208
1993.2	5,395	1.683	4,206
1993.3	6,292	1.506	3,609
1993.4	6,500	1.580	4,240
1994.1	7,096	1.688	3,601
1994.2	7,369	1.733	4,619
1994.3	8,146	1.832	4,034
1994.4	7,619	1.806	4,822
1995.1	6,818	1.927	4,290
1995.2	6,003	1.807	4,238
1995.3	5,368	1.914	3,767
1995.4	4,724	1.909	3,560
1996.1	4,267	1.736	2,932
1996.2	4,402	1.942	2,698
1996.3	4,436	1.884	2,823
1996.4	4,501	1.619	2,991
1997.1	5,035	1.668	2,541
1997.2	5,296	1.611	3,143
1997.3	5,581	1.729	3,228
1997.4	5,474	1.639	3,879

	NHUC	AHCT	NHC
1998.1	5,794	1.799	3,144
1998.2	5,930	1.703	3,873
1998.3	6,729	1.682	3,620
1998.4	6,910	1.742	3,740
1999.1	6,505	1.921	3,773
1999.2	6,487	1.918	4,173
1999.3	7,839	1.816	3,528
1999.4	8,569	1.859	3,966
2000.1	9,429	1.839	4,443
2000.2	8,375	1.966	4,783
2000.3	7,634	2.090	3,645
2000.4	6,245	2.338	4,303
2001.1	4,996	2.093	3,521
2001.2	4,649	2.105	3,044
2001.3	5,720	1.895	3,017
2001.4	6,440	1.576	3,600
2002.1	6,864	1.792	3,417
2002.2	6,771	1.852	4,044
2002.3	8,132	1.898	3,386
2002.4	7,306	1.861	4,581
2003.1	7,962	1.922	3,721
2003.2	7,859	1.982	4,015
2003.3	8,763	2.015	3,759
2003.4	9,683	2.160	3,813
2004.1	10,790	2.119	3,624
2004.2	10,787	2.293	4,346
2004.3	11,271	2.422	4,263
2004.4	12,175	2.474	3,622
2005.1	13,209	2.676	3,295
2005.2	12,985	2.883	4,706
2005.3	14,568	2.754	4,015
2005.4	14,957	2.841	4,958
2006.1	15,715	2.741	4,305
2006.2	16,176	3.079	5,098
2006.3	16,798	2.862	4,987
2006.4	16,520	3.005	5,489
2007.1	16,646	3.092	4,495
2007.2	15,057	3.089	5,982
2007.3	14,323	3.064	5,016
2007.4	13,623	3.192	4,965
2008.1	13,344	2.776	3,949
2008.2	13,145	2.997	4,808
2008.3	12,611	3.073	3,906
2008.4	11,481	3.143	4,991

South Australia:

	NHUC	AHCT	NHC		NHUC	AHCT	NHC
1987.1	2,434	1.647	1,364	**1998.1**	2,275	1.651	1,237
1987.2	2,485	1.897	1,561	**1998.2**	2,283	1.691	1,384
1987.3	2,497	1.628	1,632	**1998.3**	2,320	1.615	1,567
1987.4	2,460	1.661	1,572	**1998.4**	2,333	1.624	1,677
1988.1	2,685	1.771	1,361	**1999.1**	2,159	1.676	1,501
1988.2	2,550	1.903	1,738	**1999.2**	2,422	1.691	1,393
1988.3	2,834	1.596	1,617	**1999.3**	2,689	1.696	1,519
1988.4	3,137	1.579	1,807	**1999.4**	2,895	1.671	1,801
1989.1	3,300	1.823	1,574	**2000.1**	3,374	1.675	1,586
1989.2	3,400	1.959	1,710	**2000.2**	3,311	1.711	2,049
1989.3	3,516	1.706	1,903	**2000.3**	3,165	1.848	1,547
1989.4	3,216	1.955	1,964	**2000.4**	2,628	1.947	1,876
1990.1	3,234	1.904	1,558	**2001.1**	2,313	2.028	1,490
1990.2	3,157	2.003	1,971	**2001.2**	2,136	1.961	1,608
1990.3	3,415	1.670	1,898	**2001.3**	2,649	1.653	1,330
1990.4	3,309	1.734	2,273	**2001.4**	3,263	1.677	1,643
1991.1	3,167	1.645	2,075	**2002.1**	3,703	1.686	1,500
1991.2	3,004	1.673	2,062	**2002.2**	3,874	1.936	2,012
1991.3	2,804	1.502	2,280	**2002.3**	4,486	1.835	1,776
1991.4	2,705	1.545	2,131	**2002.4**	4,572	2.040	1,906
1992.1	2,891	1.633	1,863	**2003.1**	4,892	2.218	1,570
1992.2	2,891	1.501	2,159	**2003.2**	4,629	2.341	2,208
1992.3	3,320	1.441	1,917	**2003.3**	4,807	2.256	1,909
1992.4	3,153	1.574	2,507	**2003.4**	4,736	2.285	2,270
1993.1	3,212	1.649	2,139	**2004.1**	4,587	2.099	2,087
1993.2	3,563	1.526	2,146	**2004.2**	4,537	2.314	2,102
1993.3	3,811	1.538	2,528	**2004.3**	4,651	2.296	1,918
1993.4	3,714	1.608	2,487	**2004.4**	4,834	2.299	2,045
1994.1	3,500	1.704	2,232	**2005.1**	4,819	2.315	1,856
1994.2	3,231	1.607	2,657	**2005.2**	5,088	2.337	2,205
1994.3	3,483	1.564	2,266	**2005.3**	5,030	2.113	2,036
1994.4	3,132	1.620	2,745	**2005.4**	4,689	2.467	2,458
1995.1	2,867	1.626	1,986	**2006.1**	4,597	2.147	1,952
1995.2	2,301	1.739	2,045	**2006.2**	4,365	2.123	2,275
1995.3	2,245	1.512	1,559	**2006.3**	4,463	2.059	1,997
1995.4	2,027	1.785	1,495	**2006.4**	4,679	2.194	2,080
1996.1	1,882	1.619	1,232	**2007.1**	4,657	2.180	1,951
1996.2	1,781	1.793	1,279	**2007.2**	5,075	2.257	1,897
1996.3	1,890	1.557	1,091	**2007.3**	5,377	2.272	2,102
1996.4	1,995	1.598	1,137	**2007.4**	5,122	2.202	2,412
1997.1	2,018	1.657	1,064	**2008.1**	5,627	2.332	1,948
1997.2	2,199	1.523	1,332	**2008.2**	5,688	2.446	2,301
1997.3	2,213	1.789	1,376	**2008.3**	5,969	2.271	2,347
1997.4	2,095	1.732	1,696	**2008.4**	6,169	2.207	2,201

Average house floor area:

	NSW	Vic	Qld	SA	WA	Australia
2000-01	249	217	234	206	226	228
2001-02	236	217	224	194	225	221
2002-03	247	225	234	198	230	229
2003-04	252	229	242	198	240	235
2004-05	251	239	246	199	234	238
2005-06	266	242	252	194	238	243
2006-07	275	238	239	192	238	239

APPENDIX B - PREDICTED NUMBER OF HOUSES UNDER CONSTRUCTION

- Predicted NHUC using actual NHC with different lags
- NHC moving average
- Predicted NHUC using NHC moving average with different lags

Predicted NHUC using original number of house completion in **Victoria**

	Two quarter lag	Three quarter lag		Two quarter lag	Three quarter lag
1987.1	16,568	17,351	**1998.1**	13,235	12,885
1987.2	17,351	11,843	**1998.2**	12,885	10,885
1987.3	11,843	16,974	**1998.3**	10,885	14,729
1987.4	16,974	13,835	**1998.4**	14,729	13,330
1988.1	13,835	17,625	**1999.1**	13,330	17,220
1988.2	17,625	14,683	**1999.2**	17,220	13,631
1988.3	14,683	17,788	**1999.3**	13,631	18,413
1988.4	17,788	17,390	**1999.4**	18,413	17,287
1989.1	17,390	21,094	**2000.1**	17,287	16,278
1989.2	21,094	14,965	**2000.2**	16,278	14,165
1989.3	14,965	17,203	**2000.3**	14,165	15,664
1989.4	17,203	16,500	**2000.4**	15,664	14,083
1990.1	16,500	17,097	**2001.1**	14,083	14,454
1990.2	17,097	10,970	**2001.2**	14,454	13,773
1990.3	10,970	12,448	**2001.3**	13,773	15,309
1990.4	12,448	10,355	**2001.4**	15,309	17,907
1991.1	10,355	11,880	**2002.1**	17,907	20,945
1991.2	11,880	11,457	**2002.2**	20,945	15,904
1991.3	11,457	12,432	**2002.3**	15,904	19,802
1991.4	12,432	10,652	**2002.4**	19,802	16,582
1992.1	10,652	11,623	**2003.1**	16,582	19,465
1992.2	11,623	11,574	**2003.2**	19,465	15,765
1992.3	11,574	11,410	**2003.3**	15,765	19,728
1992.4	11,410	13,454	**2003.4**	19,728	22,216
1993.1	13,454	11,139	**2004.1**	22,216	18,624
1993.2	11,139	10,383	**2004.2**	18,624	15,390
1993.3	10,383	12,306	**2004.3**	15,390	18,836
1993.4	12,306	12,508	**2004.4**	18,836	20,478
1994.1	12,508	14,259	**2005.1**	20,478	20,339
1994.2	14,259	11,404	**2005.2**	20,339	15,091
1994.3	11,404	12,194	**2005.3**	15,091	14,661
1994.4	12,194	10,679	**2005.4**	14,661	14,319
1995.1	10,679	11,660	**2006.1**	14,319	18,321
1995.2	11,660	8,898	**2006.2**	18,321	19,257
1995.3	8,898	8,168	**2006.3**	19,257	18,197
1995.4	8,168	7,073	**2006.4**	18,197	18,571
1996.1	7,073	9,979	**2007.1**	18,571	17,256
1996.2	9,979	7,974	**2007.2**	17,256	15,465
1996.3	7,974	8,005	**2007.3**	15,465	17,269
1996.4	8,005	8,775	**2007.4**	17,269	19,024
1997.1	8,775	9,879	**2008.1**	19,024	22,449
1997.2	9,879	9,263	**2008.2**	22,449	
1997.3	9,263	11,505	**2008.3**		
1997.4	11,505	13,235	**2008.4**		

Number of house completion moving average in **Victoria**

	NHC moving average		NHC moving average
1987.1	6,381	**1998.1**	5,218
1987.2	6,563	**1998.2**	5,606
1987.3	6,688	**1998.3**	6,069
1987.4	6,914	**1998.4**	6,357
1988.1	6,695	**1999.1**	6,471
1988.2	6,918	**1999.2**	6,732
1988.3	6,943	**1999.3**	6,729
1988.4	7,133	**1999.4**	7,160
1989.1	7,472	**2000.1**	7,377
1989.2	7,634	**2000.2**	7,808
1989.3	7,890	**2000.3**	8,129
1989.4	8,122	**2000.4**	7,906
1990.1	8,036	**2001.1**	7,797
1990.2	7,937	**2001.2**	7,220
1990.3	7,654	**2001.3**	6,839
1990.4	7,277	**2001.4**	6,676
1991.1	6,877	**2002.1**	6,831
1991.2	6,304	**2002.2**	7,169
1991.3	5,832	**2002.3**	7,569
1991.4	5,410	**2002.4**	8,209
1992.1	5,457	**2003.1**	8,388
1992.2	5,600	**2003.2**	8,542
1992.3	5,830	**2003.3**	8,387
1992.4	5,918	**2003.4**	8,085
1993.1	6,181	**2004.1**	7,971
1993.2	6,275	**2004.2**	7,874
1993.3	6,611	**2004.3**	8,158
1993.4	6,727	**2004.4**	7,937
1994.1	6,686	**2005.1**	7,891
1994.2	6,780	**2005.2**	7,583
1994.3	6,699	**2005.3**	7,650
1994.4	6,976	**2005.4**	7,847
1995.1	7,057	**2006.1**	7,714
1995.2	6,845	**2006.2**	7,608
1995.3	6,666	**2006.3**	6,961
1995.4	6,324	**2006.4**	6,807
1996.1	5,892	**2007.1**	7,092
1996.2	5,471	**2007.2**	7,217
1996.3	4,866	**2007.3**	7,548
1996.4	4,476	**2007.4**	7,468
1997.1	4,330	**2008.1**	7,061
1997.2	4,403	**2008.2**	7,055
1997.3	4,717	**2008.3**	6,926
1997.4	4,907	**2008.4**	7,322

Predicted NHUC using number of house completion moving average in **Victoria**

	Two quarter lag	Three quarter lag		Two quarter lag	Three quarter lag
1987.1	15,971	15,804	**1998.1**	11,554	11,709
1987.2	15,804	14,400	**1998.2**	11,709	12,360
1987.3	14,400	15,372	**1998.3**	12,360	13,618
1987.4	15,372	13,650	**1998.4**	13,618	12,925
1988.1	13,650	15,057	**1999.1**	12,925	14,140
1988.2	15,057	15,989	**1999.2**	14,140	15,307
1988.3	15,989	16,383	**1999.3**	15,307	15,967
1988.4	16,383	17,019	**1999.4**	15,967	17,087
1989.1	17,019	18,469	**2000.1**	17,087	16,444
1989.2	18,469	18,458	**2000.2**	16,444	18,010
1989.3	18,458	17,295	**2000.3**	18,010	16,887
1989.4	17,295	18,224	**2000.4**	16,887	14,375
1990.1	18,224	16,017	**2001.1**	14,375	13,451
1990.2	16,017	15,349	**2001.2**	13,451	13,929
1990.3	15,349	14,007	**2001.3**	13,929	13,636
1990.4	14,007	11,974	**2001.4**	13,636	16,333
1991.1	11,974	10,572	**2002.1**	16,333	17,665
1991.2	10,572	12,256	**2002.2**	17,665	17,857
1991.3	12,256	11,273	**2002.3**	17,857	19,518
1991.4	11,273	10,413	**2002.4**	19,518	18,115
1992.1	10,413	10,694	**2003.1**	18,115	18,457
1992.2	10,694	11,627	**2003.2**	18,457	17,911
1992.3	11,627	10,931	**2003.3**	17,911	18,770
1992.4	10,931	12,170	**2003.4**	18,770	20,559
1993.1	12,170	10,864	**2004.1**	20,559	19,349
1993.2	10,864	11,593	**2004.2**	19,349	17,771
1993.3	11,593	12,047	**2004.3**	17,771	20,278
1993.4	12,047	11,997	**2004.4**	20,278	17,250
1994.1	11,997	12,424	**2005.1**	17,250	18,935
1994.2	12,424	12,751	**2005.2**	18,935	18,474
1994.3	12,751	13,731	**2005.3**	18,474	16,845
1994.4	13,731	11,358	**2005.4**	16,845	15,355
1995.1	11,358	11,105	**2006.1**	15,355	15,962
1995.2	11,105	11,442	**2006.2**	15,962	18,353
1995.3	11,442	10,170	**2006.3**	18,353	18,439
1995.4	10,170	8,944	**2006.4**	18,439	17,934
1996.1	8,944	8,791	**2007.1**	17,934	17,199
1996.2	8,791	8,638	**2007.2**	17,199	18,783
1996.3	8,638	7,521	**2007.3**	18,783	17,165
1996.4	7,521	8,113	**2007.4**	17,165	18,050
1997.1	8,113	8,298	**2008.1**	18,050	18,113
1997.2	8,298	9,221	**2008.2**	18,113	
1997.3	9,221	10,338	**2008.3**		
1997.4	10,338	11,554	**2008.4**		

***Predicted NHUC using original number of house completions in* Western Australia**

	Two quarter lag	Three quarter lag
1987.1	4,987	6,078
1987.2	6,078	4,807
1987.3	4,807	4,674
1987.4	4,674	5,224
1988.1	5,224	8,178
1988.2	8,178	6,834
1988.3	6,834	9,478
1988.4	9,478	10,724
1989.1	10,724	12,332
1989.2	12,332	10,726
1989.3	10,726	7,467
1989.4	7,467	5,978
1990.1	5,978	5,945
1990.2	5,945	4,904
1990.3	4,904	4,987
1990.4	4,987	4,626
1991.1	4,626	5,576
1991.2	5,576	4,655
1991.3	4,655	4,837
1991.4	4,837	4,675
1992.1	4,675	6,353
1992.2	6,353	4,998
1992.3	4,998	7,079
1992.4	7,079	5,435
1993.1	5,435	6,699
1993.2	6,699	6,078
1993.3	6,078	8,005
1993.4	8,005	7,390
1994.1	7,390	8,709
1994.2	8,709	8,267
1994.3	8,267	7,658
1994.4	7,658	7,210
1995.1	7,210	6,796
1995.2	6,796	5,090
1995.3	5,090	5,240
1995.4	5,240	5,319
1996.1	5,319	4,842
1996.2	4,842	4,238
1996.3	4,238	5,063
1996.4	5,063	5,581
1997.1	5,581	6,358
1997.2	6,358	5,656
1997.3	5,656	6,596
1997.4	6,596	6,089

	Two quarter lag	Three quarter lag
1998.1	6,089	6,515
1998.2	6,515	7,248
1998.3	7,248	8,004
1998.4	8,004	6,407
1999.1	6,407	7,373
1999.2	7,373	8,171
1999.3	8,171	9,403
1999.4	9,403	7,618
2000.1	7,618	10,060
2000.2	10,060	7,369
2000.3	7,369	6,408
2000.4	6,408	5,717
2001.1	5,717	5,674
2001.2	5,674	6,123
2001.3	6,123	7,489
2001.4	7,489	6,427
2002.1	6,427	8,525
2002.2	8,525	7,152
2002.3	7,152	7,958
2002.4	7,958	7,574
2003.1	7,574	8,236
2003.2	8,236	7,679
2003.3	7,679	9,965
2003.4	9,965	10,325
2004.1	10,325	8,961
2004.2	8,961	8,817
2004.3	8,817	13,567
2004.4	13,567	11,057
2005.1	11,057	14,086
2005.2	14,086	11,800
2005.3	11,800	15,697
2005.4	15,697	14,273
2006.1	14,273	16,494
2006.2	16,494	13,899
2006.3	13,899	18,478
2006.4	18,478	15,369
2007.1	15,369	15,848
2007.2	15,848	10,962
2007.3	10,962	14,410
2007.4	14,410	12,003
2008.1	12,003	15,687
2008.2	15,687	
2008.3		
2008.4		

Number of house completions moving average in **Western Australia**

	NHC moving average		NHC moving average
1987.1	3,097	**1998.1**	3,512
1987.2	3,115	**1998.2**	3,509
1987.3	3,078	**1998.3**	3,747
1987.4	3,342	**1998.4**	3,680
1988.1	3,306	**1999.1**	3,757
1988.2	2,855	**1999.2**	3,973
1988.3	2,842	**1999.3**	3,851
1988.4	3,620	**1999.4**	3,747
1989.1	3,781	**2000.1**	4,205
1989.2	3,711	**2000.2**	4,613
1989.3	4,378	**2000.3**	4,214
1989.4	4,948	**2000.4**	3,974
1990.1	4,780	**2001.1**	3,912
1990.2	3,896	**2001.2**	3,283
1990.3	3,267	**2001.3**	3,031
1990.4	2,982	**2001.4**	3,309
1991.1	2,856	**2002.1**	3,509
1991.2	2,711	**2002.2**	3,731
1991.3	2,627	**2002.3**	3,715
1991.4	2,914	**2002.4**	3,984
1992.1	3,018	**2003.1**	4,151
1992.2	2,856	**2003.2**	3,868
1992.3	2,938	**2003.3**	3,887
1992.4	3,477	**2003.4**	3,786
1993.1	3,610	**2004.1**	3,719
1993.2	3,707	**2004.2**	3,985
1993.3	3,908	**2004.3**	4,305
1993.4	3,925	**2004.4**	3,943
1994.1	3,921	**2005.1**	3,459
1994.2	4,110	**2005.2**	4,001
1994.3	4,327	**2005.3**	4,361
1994.4	4,428	**2005.4**	4,487
1995.1	4,556	**2006.1**	4,632
1995.2	4,264	**2006.2**	4,702
1995.3	4,003	**2006.3**	5,043
1995.4	3,664	**2006.4**	5,238
1996.1	3,246	**2007.1**	4,992
1996.2	2,815	**2007.2**	5,239
1996.3	2,761	**2007.3**	5,499
1996.4	2,907	**2007.4**	4,991
1997.1	2,766	**2008.1**	4,457
1997.2	2,842	**2008.2**	4,379
1997.3	3,186	**2008.3**	4,357
1997.4	3,554	**2008.4**	4,449

***Predicted NHUC using number of house completions moving average in* Western Australia**

	Two quarter lag	Three quarter lag
1987.1	5,076	5,550
1987.2	5,550	5,382
1987.3	5,382	4,841
1987.4	4,841	5,070
1988.1	5,070	6,866
1988.2	6,866	7,948
1988.3	7,948	8,434
1988.4	8,434	10,239
1989.1	10,239	11,489
1989.2	11,489	12,068
1989.3	12,068	8,209
1989.4	8,209	6,533
1990.1	6,533	5,960
1990.2	5,960	5,115
1990.3	5,115	5,037
1990.4	5,037	4,729
1991.1	4,729	4,988
1991.2	4,988	5,055
1991.3	5,055	4,710
1991.4	4,710	4,668
1992.1	4,668	5,507
1992.2	5,507	5,624
1992.3	5,624	6,239
1992.4	6,239	5,885
1993.1	5,885	6,201
1993.2	6,201	6,618
1993.3	6,618	7,123
1993.4	7,123	7,926
1994.1	7,926	7,997
1994.2	7,997	8,779
1994.3	8,779	7,705
1994.4	7,705	7,661
1995.1	7,661	6,994
1995.2	6,994	5,635
1995.3	5,635	5,467
1995.4	5,467	5,201
1996.1	5,201	4,706
1996.2	4,706	4,614
1996.3	4,614	4,578
1996.4	4,578	5,508
1997.1	5,508	5,824
1997.2	5,824	6,317
1997.3	6,317	5,975
1997.4	5,975	6,302

	Two quarter lag	Three quarter lag
1998.1	6,302	6,411
1998.2	6,411	7,216
1998.3	7,216	7,620
1998.4	7,620	6,993
1999.1	6,993	6,966
1999.2	6,966	7,732
1999.3	7,732	9,069
1999.4	9,069	8,807
2000.1	8,807	9,291
2000.2	9,291	8,188
2000.3	8,188	6,910
2000.4	6,910	5,743
2001.1	5,743	5,214
2001.2	5,214	6,287
2001.3	6,287	6,909
2001.4	6,909	7,051
2002.1	7,051	7,413
2002.2	7,413	7,978
2002.3	7,978	7,666
2002.4	7,666	7,832
2003.1	7,832	8,178
2003.2	8,178	7,880
2003.3	7,880	9,138
2003.4	9,138	10,425
2004.1	10,425	9,754
2004.2	9,754	9,255
2004.3	9,255	11,533
2004.4	11,533	12,009
2005.1	12,009	12,746
2005.2	12,746	12,695
2005.3	12,695	14,476
2005.4	14,476	14,432
2006.1	14,432	15,740
2006.2	15,740	15,435
2006.3	15,435	16,182
2006.4	16,182	16,849
2007.1	16,849	15,930
2007.2	15,930	12,373
2007.3	12,373	13,122
2007.4	13,122	13,389
2008.1	13,389	13,982
2008.2	13,982	
2008.3		
2008.4		

***Predicted NHUC using original number of house completion in* South Australia**

	Two quarter lag	Three quarter lag
1987.1	2,657	2,611
1987.2	2,611	2,410
1987.3	2,410	3,307
1987.4	3,307	2,581
1988.1	2,581	2,853
1988.2	2,853	2,869
1988.3	2,869	3,350
1988.4	3,350	3,247
1989.1	3,247	3,840
1989.2	3,840	2,966
1989.3	2,966	3,948
1989.4	3,948	3,170
1990.1	3,170	3,941
1990.2	3,941	3,413
1990.3	3,413	3,450
1990.4	3,450	3,425
1991.1	3,425	3,292
1991.2	3,292	3,042
1991.3	3,042	3,241
1991.4	3,241	2,762
1992.1	2,762	3,946
1992.2	3,946	3,527
1992.3	3,527	3,275
1992.4	3,275	3,888
1993.1	3,888	3,999
1993.2	3,999	3,803
1993.3	3,803	4,270
1993.4	4,270	3,544
1994.1	3,544	4,447
1994.2	4,447	3,229
1994.3	3,229	3,556
1994.4	3,556	2,357
1995.1	2,357	2,669
1995.2	2,669	1,995
1995.3	1,995	2,293
1995.4	2,293	1,699
1996.1	1,699	1,817
1996.2	1,817	1,763
1996.3	1,763	2,029
1996.4	2,029	2,462
1997.1	2,462	2,937
1997.2	2,937	2,042
1997.3	2,042	2,340
1997.4	2,340	2,531

	Two quarter lag	Three quarter lag
1998.1	2,531	2,723
1998.2	2,723	2,516
1998.3	2,516	2,356
1998.4	2,356	2,576
1999.1	2,576	3,009
1999.2	3,009	2,657
1999.3	2,657	3,506
1999.4	3,506	2,859
2000.1	2,859	3,653
2000.2	3,653	3,022
2000.3	3,022	3,153
2000.4	3,153	2,198
2001.1	2,198	2,755
2001.2	2,755	2,529
2001.3	2,529	3,895
2001.4	3,895	3,259
2002.1	3,259	3,888
2002.2	3,888	3,482
2002.3	3,482	5,169
2002.4	5,169	4,307
2003.1	4,307	5,187
2003.2	5,187	4,381
2003.3	4,381	4,864
2003.4	4,864	4,404
2004.1	4,404	4,701
2004.2	4,701	4,297
2004.3	4,297	5,153
2004.4	5,153	4,302
2005.1	4,302	6,064
2005.2	6,064	4,191
2005.3	4,191	4,830
2005.4	4,830	4,112
2006.1	4,112	4,564
2006.2	4,564	4,253
2006.3	4,253	4,282
2006.4	4,282	4,776
2007.1	4,776	5,311
2007.2	5,311	4,543
2007.3	4,543	5,628
2007.4	5,628	5,330
2008.1	5,330	4,858
2008.2	4,858	
2008.3		
2008.4		

Number of house completion moving average in **South Australia**

	NHC moving average
1987.1	1,364
1987.2	1,463
1987.3	1,597
1987.4	1,602
1988.1	1,467
1988.2	1,550
1988.3	1,678
1988.4	1,712
1989.1	1,691
1989.2	1,642
1989.3	1,807
1989.4	1,934
1990.1	1,761
1990.2	1,765
1990.3	1,935
1990.4	2,086
1991.1	2,174
1991.2	2,069
1991.3	2,171
1991.4	2,206
1992.1	1,997
1992.2	2,011
1992.3	2,038
1992.4	2,212
1993.1	2,323
1993.2	2,143
1993.3	2,337
1993.4	2,508
1994.1	2,360
1994.2	2,445
1994.3	2,462
1994.4	2,506
1995.1	2,366
1995.2	2,016
1995.3	1,802
1995.4	1,527
1996.1	1,364
1996.2	1,256
1996.3	1,185
1996.4	1,114
1997.1	1,101
1997.2	1,198
1997.3	1,354
1997.4	1,536
1998.1	1,467
1998.2	1,311
1998.3	1,476
1998.4	1,622
1999.1	1,589
1999.2	1,447
1999.3	1,456
1999.4	1,660
2000.1	1,694
2000.2	1,818
2000.3	1,798
2000.4	1,712
2001.1	1,683
2001.2	1,549
2001.3	1,469
2001.4	1,487
2002.1	1,572
2002.2	1,756
2002.3	1,894
2002.4	1,841
2003.1	1,738
2003.2	1,889
2003.3	2,059
2003.4	2,090
2004.1	2,179
2004.2	2,095
2004.3	2,010
2004.4	1,982
2005.1	1,951
2005.2	2,031
2005.3	2,121
2005.4	2,247
2006.1	2,205
2006.2	2,114
2006.3	2,136
2006.4	2,039
2007.1	2,016
2007.2	1,924
2007.3	2,000
2007.4	2,257
2008.1	2,180
2008.2	2,125
2008.3	2,324
2008.4	2,274

Predicted NHUC using number of house completion moving average in **South Australia**

	Two quarter lag	Three quarter lag		Two quarter lag	Three quarter lag
1987.1	2,599	2,661	**1998.1**	2,383	2,634
1987.2	2,661	2,597	**1998.2**	2,634	2,663
1987.3	2,597	2,949	**1998.3**	2,663	2,447
1987.4	2,949	2,677	**1998.4**	2,447	2,469
1988.1	2,677	2,703	**1999.1**	2,469	2,774
1988.2	2,703	3,082	**1999.2**	2,774	2,837
1988.3	3,082	3,217	**1999.3**	2,837	3,110
1988.4	3,217	3,082	**1999.4**	3,110	3,323
1989.1	3,082	3,780	**2000.1**	3,323	3,332
1989.2	3,780	3,353	**2000.2**	3,332	3,413
1989.3	3,353	3,534	**2000.3**	3,413	3,038
1989.4	3,534	3,231	**2000.4**	3,038	2,428
1990.1	3,231	3,616	**2001.1**	2,428	2,493
1990.2	3,616	3,576	**2001.2**	2,493	2,650
1990.3	3,576	3,461	**2001.3**	2,650	3,400
1990.4	3,461	3,261	**2001.4**	3,400	3,475
1991.1	3,261	3,407	**2002.1**	3,475	3,756
1991.2	3,407	3,261	**2002.2**	3,756	3,855
1991.3	3,261	3,019	**2002.3**	3,855	4,422
1991.4	3,019	2,937	**2002.4**	4,422	4,644
1992.1	2,937	3,482	**2003.1**	4,644	4,775
1992.2	3,482	3,831	**2003.2**	4,775	4,573
1992.3	3,831	3,269	**2003.3**	4,573	4,847
1992.4	3,269	3,594	**2003.4**	4,847	4,615
1993.1	3,594	4,032	**2004.1**	4,615	4,555
1993.2	4,032	4,021	**2004.2**	4,555	4,515
1993.3	4,021	3,928	**2004.3**	4,515	4,745
1993.4	3,928	3,850	**2004.4**	4,745	4,481
1994.1	3,850	4,059	**2005.1**	4,481	5,543
1994.2	4,059	3,846	**2005.2**	5,543	4,734
1994.3	3,846	3,505	**2005.3**	4,734	4,487
1994.4	3,505	2,725	**2005.4**	4,487	4,398
1995.1	2,725	2,726	**2006.1**	4,398	4,472
1995.2	2,726	2,208	**2006.2**	4,472	4,394
1995.3	2,208	2,251	**2006.3**	4,394	4,342
1995.4	2,251	1,845	**2006.4**	4,342	4,543
1996.1	1,845	1,780	**2007.1**	4,543	4,970
1996.2	1,780	1,824	**2007.2**	4,970	5,084
1996.3	1,824	1,825	**2007.3**	5,084	5,197
1996.4	1,825	2,422	**2007.4**	5,197	5,278
1997.1	2,422	2,660	**2008.1**	5,278	5,019
1997.2	2,660	2,421	**2008.2**	5,019	
1997.3	2,421	2,216	**2008.3**		
1997.4	2,216	2,383	**2008.4**		

Predicted NHUC using original number of house completion in **New South Wales**

	Two quarter lag	Three quarter lag
1987.1	9,331	11,171
1987.2	11,171	11,234
1987.3	11,234	14,673
1987.4	14,673	15,352
1988.1	15,352	19,200
1988.2	19,200	14,177
1988.3	14,177	19,751
1988.4	19,751	20,012
1989.1	20,012	19,794
1989.2	19,794	14,980
1989.3	14,980	14,213
1989.4	14,213	15,093
1990.1	15,093	16,609
1990.2	16,609	11,811
1990.3	11,811	15,225
1990.4	15,225	12,961
1991.1	12,961	13,470
1991.2	13,470	11,761
1991.3	11,761	13,304
1991.4	13,304	12,350
1992.1	12,350	15,184
1992.2	15,184	12,618
1992.3	12,618	12,222
1992.4	12,222	11,421
1993.1	11,421	15,847
1993.2	15,847	13,694
1993.3	13,694	11,036
1993.4	11,036	13,990
1994.1	13,990	15,093
1994.2	15,093	12,351
1994.3	12,351	13,529
1994.4	13,529	13,917
1995.1	13,917	12,847
1995.2	12,847	12,105
1995.3	12,105	11,476
1995.4	11,476	10,821
1996.1	10,821	10,197
1996.2	10,197	10,590
1996.3	10,590	10,810
1996.4	10,810	10,142
1997.1	10,142	12,032
1997.2	12,032	9,606
1997.3	9,606	12,817
1997.4	12,817	11,824

	Two quarter lag	Three quarter lag
1998.1	11,824	12,747
1998.2	12,747	10,253
1998.3	10,253	12,922
1998.4	12,922	11,277
1999.1	11,277	14,528
1999.2	14,528	12,663
1999.3	12,663	15,373
1999.4	15,373	14,049
2000.1	14,049	14,465
2000.2	14,465	10,051
2000.3	10,051	9,346
2000.4	9,346	8,710
2001.1	8,710	10,607
2001.2	10,607	10,016
2001.3	10,016	11,699
2001.4	11,699	9,829
2002.1	9,829	14,660
2002.2	14,660	11,528
2002.3	11,528	11,414
2002.4	11,414	11,370
2003.1	11,370	13,397
2003.2	13,397	11,162
2003.3	11,162	13,938
2003.4	13,938	12,570
2004.1	12,570	12,710
2004.2	12,710	10,988
2004.3	10,988	11,590
2004.4	11,590	14,160
2005.1	14,160	12,732
2005.2	12,732	8,022
2005.3	8,022	9,553
2005.4	9,553	8,304
2006.1	8,304	9,531
2006.2	9,531	8,571
2006.3	8,571	8,913
2006.4	8,913	8,155
2007.1	8,155	9,477
2007.2	9,477	7,667
2007.3	7,667	8,026
2007.4	8,026	8,631
2008.1	8,631	10,956
2008.2	10,956	
2008.3		
2008.4		

Number of house completion moving average in **New South Wales**

	NHC moving average		NHC moving average
1987.1	4,774	**1998.1**	6,357
1987.2	4,845	**1998.2**	6,295
1987.3	4,871	**1998.3**	6,747
1987.4	5,209	**1998.4**	6,912
1988.1	5,499	**1999.1**	6,357
1988.2	5,945	**1999.2**	6,247
1988.3	6,680	**1999.3**	6,596
1988.4	7,819	**1999.4**	6,769
1989.1	7,524	**2000.1**	7,087
1989.2	7,440	**2000.2**	7,507
1989.3	8,523	**2000.3**	7,707
1989.4	8,351	**2000.4**	6,955
1990.1	7,270	**2001.1**	5,587
1990.2	6,232	**2001.2**	4,591
1990.3	6,149	**2001.3**	4,702
1990.4	6,638	**2001.4**	5,228
1991.1	6,453	**2002.1**	5,446
1991.2	6,115	**2002.2**	5,563
1991.3	6,218	**2002.3**	5,611
1991.4	6,339	**2002.4**	6,376
1992.1	6,338	**2003.1**	6,607
1992.2	6,289	**2003.2**	5,460
1992.3	6,716	**2003.3**	5,356
1992.4	7,163	**2003.4**	5,763
1993.1	6,976	**2004.1**	5,433
1993.2	6,429	**2004.2**	5,398
1993.3	6,652	**2004.3**	5,896
1993.4	7,682	**2004.4**	5,663
1994.1	7,663	**2005.1**	5,140
1994.2	6,634	**2005.2**	4,708
1994.3	7,043	**2005.3**	5,068
1994.4	8,114	**2005.4**	5,437
1995.1	7,401	**2006.1**	4,431
1995.2	6,534	**2006.2**	3,694
1995.3	7,004	**2006.3**	3,822
1995.4	6,986	**2006.4**	3,872
1996.1	6,361	**2007.1**	3,896
1996.2	6,036	**2007.2**	3,785
1996.3	6,068	**2007.3**	3,661
1996.4	6,022	**2007.4**	3,581
1997.1	5,807	**2008.1**	3,402
1997.2	5,709	**2008.2**	3,260
1997.3	5,784	**2008.3**	3,507
1997.4	6,398	**2008.4**	3,916

Predicted NHUC using number of house completion moving average in **New South Wales**

	Two quarter lag	Three quarter lag
1987.1	9,416	10,408
1987.2	10,408	11,426
1987.3	11,426	13,454
1987.4	13,454	14,915
1988.1	14,915	17,131
1988.2	17,131	16,973
1988.3	16,973	17,096
1988.4	17,096	20,182
1989.1	20,182	20,034
1989.2	20,034	17,317
1989.3	17,317	14,345
1989.4	14,345	15,156
1990.1	15,156	15,413
1990.2	15,413	13,248
1990.3	13,248	14,375
1990.4	14,375	13,523
1991.1	13,523	12,709
1991.2	12,709	12,511
1991.3	12,511	12,640
1991.4	12,640	12,175
1992.1	12,175	14,475
1992.2	14,475	13,672
1992.3	13,672	12,240
1992.4	12,240	11,035
1993.1	11,035	14,357
1993.2	14,357	15,326
1993.3	15,326	11,403
1993.4	11,403	12,853
1994.1	12,853	14,304
1994.2	14,304	14,647
1994.3	14,647	12,949
1994.4	12,949	13,573
1995.1	13,573	13,217
1995.2	13,217	12,982
1995.3	12,982	11,280
1995.4	11,280	10,952
1996.1	10,952	10,152
1996.2	10,152	11,050
1996.3	11,050	10,545
1996.4	10,545	10,266
1997.1	10,266	10,870
1997.2	10,870	10,844
1997.3	10,844	11,594
1997.4	11,594	12,205

	Two quarter lag	Three quarter lag
1998.1	12,205	12,089
1998.2	12,089	12,014
1998.3	12,014	11,420
1998.4	11,420	12,149
1999.1	12,149	13,260
1999.2	13,260	13,280
1999.3	13,280	13,977
1999.4	13,977	15,128
2000.1	15,128	14,898
2000.2	14,898	12,704
2000.3	12,704	9,011
2000.4	9,011	8,821
2001.1	8,821	9,540
2001.2	9,540	10,739
2001.3	10,739	10,763
2001.4	10,763	10,655
2002.1	10,655	12,338
2002.2	12,338	13,510
2002.3	13,510	11,798
2002.4	11,798	11,215
2003.1	11,215	12,666
2003.2	12,666	12,712
2003.3	12,712	12,486
2003.4	12,486	12,853
2004.1	12,853	12,946
2004.2	12,946	11,966
2004.3	11,966	11,619
2004.4	11,619	13,192
2005.1	13,192	12,739
2005.2	12,739	10,369
2005.3	10,369	8,912
2005.4	8,912	8,614
2006.1	8,614	9,090
2006.2	9,090	8,945
2006.3	8,945	8,793
2006.4	8,793	8,567
2007.1	8,567	9,231
2007.2	9,231	8,338
2007.3	8,338	7,715
2007.4	7,715	8,356
2008.1	8,356	10,192
2008.2	10,192	
2008.3		
2008.4		

***Predicted NHUC using original number of house completion in* Queensland**

	Two quarter lag	Three quarter lag
1987.1	5,482	6,678
1987.2	6,678	7,300
1987.3	7,300	7,071
1987.4	7,071	9,213
1988.1	9,213	11,795
1988.2	11,795	10,337
1988.3	10,337	10,662
1988.4	10,662	12,087
1989.1	12,087	11,059
1989.2	11,059	10,162
1989.3	10,162	8,045
1989.4	8,045	8,220
1990.1	8,220	8,190
1990.2	8,190	7,435
1990.3	7,435	7,334
1990.4	7,334	8,897
1991.1	8,897	8,943
1991.2	8,943	8,811
1991.3	8,811	7,783
1991.4	7,783	9,610
1992.1	9,610	13,787
1992.2	13,787	10,767
1992.3	10,767	11,476
1992.4	11,476	11,567
1993.1	11,567	15,492
1993.2	15,492	11,084
1993.3	11,084	9,679
1993.4	9,679	11,521
1994.1	11,521	13,604
1994.2	13,604	10,414
1994.3	10,414	10,019
1994.4	10,019	8,810
1995.1	8,810	8,979
1995.2	8,979	6,924
1995.3	6,924	7,226
1995.4	7,226	7,640
1996.1	7,640	7,987
1996.2	7,987	6,938
1996.3	6,938	7,209
1996.4	7,209	7,970
1997.1	7,970	8,474
1997.2	8,474	6,924
1997.3	6,924	7,733
1997.4	7,733	9,213

	Two quarter lag	Three quarter lag
1998.1	9,213	7,330
1998.2	7,330	5,210
1998.3	5,210	6,552
1998.4	6,552	7,567
1999.1	7,567	6,812
1999.2	6,812	7,364
1999.3	7,364	10,556
1999.4	10,556	7,511
2000.1	7,511	5,142
2000.2	5,142	4,521
2000.3	4,521	4,584
2000.4	4,584	5,592
2001.1	5,592	7,415
2001.2	7,415	6,551
2001.3	6,551	9,363
2001.4	9,363	9,452
2002.1	9,452	9,397
2002.2	9,397	10,353
2002.3	10,353	8,734
2002.4	8,734	10,585
2003.1	10,585	10,048
2003.2	10,048	9,585
2003.3	9,585	11,934
2003.4	11,934	13,137
2004.1	13,137	12,733
2004.2	12,733	11,318
2004.3	11,318	13,659
2004.4	13,659	11,143
2005.1	11,143	11,289
2005.2	11,289	8,301
2005.3	8,301	10,224
2005.4	10,224	8,723
2006.1	8,723	13,135
2006.2	13,135	10,688
2006.3	10,688	14,213
2006.4	14,213	11,639
2007.1	11,639	15,698
2007.2	15,698	11,446
2007.3	11,446	15,267
2007.4	15,267	15,505
2008.1	15,505	16,627
2008.2	16,627	
2008.3		
2008.4		

Number of house completion moving average in **Queensland**

	NHC moving average		NHC moving average
1987.1	3,641	**1998.1**	5,817
1987.2	4,023	**1998.2**	5,843
1987.3	4,152	**1998.3**	5,923
1987.4	4,373	**1998.4**	5,697
1988.1	4,664	**1999.1**	5,444
1988.2	4,852	**1999.2**	5,193
1988.3	5,429	**1999.3**	5,048
1988.4	6,266	**1999.4**	4,984
1989.1	6,629	**2000.1**	5,297
1989.2	7,050	**2000.2**	6,039
1989.3	7,269	**2000.3**	5,949
1989.4	7,028	**2000.4**	5,562
1990.1	7,115	**2001.1**	5,089
1990.2	6,763	**2001.2**	4,091
1990.3	6,361	**2001.3**	3,907
1990.4	6,080	**2001.4**	4,453
1991.1	5,728	**2002.1**	4,848
1991.2	5,747	**2002.2**	5,539
1991.3	5,970	**2002.3**	6,021
1991.4	6,258	**2002.4**	6,107
1992.1	6,616	**2003.1**	6,534
1992.2	6,776	**2003.2**	6,268
1992.3	6,942	**2003.3**	6,351
1992.4	7,582	**2003.4**	6,542
1993.1	7,810	**2004.1**	6,298
1993.2	8,400	**2004.2**	6,660
1993.3	8,703	**2004.3**	6,773
1993.4	8,837	**2004.4**	6,673
1994.1	8,837	**2005.1**	6,734
1994.2	8,698	**2005.2**	6,890
1994.3	8,677	**2005.3**	6,679
1994.4	8,589	**2005.4**	6,752
1995.1	8,633	**2006.1**	6,483
1995.2	8,382	**2006.2**	6,036
1995.3	7,778	**2006.3**	5,750
1995.4	6,944	**2006.4**	5,730
1996.1	6,262	**2007.1**	5,985
1996.2	5,963	**2007.2**	6,414
1996.3	5,781	**2007.3**	6,616
1996.4	5,655	**2007.4**	6,926
1997.1	5,654	**2008.1**	6,880
1997.2	5,638	**2008.2**	6,813
1997.3	5,734	**2008.3**	7,135
1997.4	5,799	**2008.4**	7,140

***Predicted NHUC using number of house completion moving average in* Queensland**

	Two quarter lag	Three quarter lag
1987.1	5,161	5,798
1987.2	5,798	7,085
1987.3	7,085	6,656
1987.4	6,656	7,443
1988.1	7,443	8,816
1988.2	8,816	10,950
1988.3	10,950	10,991
1988.4	10,991	11,565
1989.1	11,565	10,478
1989.2	10,478	10,943
1989.3	10,943	10,016
1989.4	10,016	8,733
1990.1	8,733	7,910
1990.2	7,910	8,191
1990.3	8,191	7,655
1990.4	7,655	7,720
1991.1	7,720	7,516
1991.2	7,516	8,792
1991.3	8,792	8,579
1991.4	8,579	8,844
1992.1	8,844	10,447
1992.2	10,447	11,145
1992.3	11,145	11,332
1992.4	11,332	11,497
1993.1	11,497	12,990
1993.2	12,990	12,981
1993.3	12,981	10,586
1993.4	10,586	11,531
1994.1	11,531	11,467
1994.2	11,467	11,646
1994.3	11,646	12,086
1994.4	12,086	10,959
1995.1	10,959	9,096
1995.2	9,096	8,685
1995.3	8,685	7,490
1995.4	7,490	7,995
1996.1	7,995	7,113
1996.2	7,113	7,864
1996.3	7,864	7,143
1996.4	7,143	7,735
1997.1	7,735	7,434
1997.2	7,434	7,963
1997.3	7,963	7,795
1997.4	7,795	8,765

	Two quarter lag	Three quarter lag
1998.1	8,765	7,315
1998.2	7,315	7,012
1998.3	7,012	7,099
1998.4	7,099	6,769
1999.1	6,769	6,225
1999.2	6,225	7,363
1999.3	7,363	8,213
1999.4	8,213	8,459
2000.1	8,459	7,320
2000.2	7,320	6,758
2000.3	6,758	4,974
2000.4	4,974	4,805
2001.1	4,805	5,420
2001.2	5,420	6,375
2001.3	6,375	7,937
2001.4	7,937	8,790
2002.1	8,790	8,915
2002.2	8,915	10,108
2002.3	10,108	10,010
2002.4	10,010	9,876
2003.1	9,876	9,132
2003.2	9,132	10,556
2003.3	10,556	11,494
2003.4	11,494	12,253
2004.1	12,253	12,499
2004.2	12,499	12,787
2004.3	12,787	12,484
2004.4	12,484	11,594
2005.1	11,594	10,749
2005.2	10,749	11,021
2005.3	11,021	10,732
2005.4	10,732	9,505
2006.1	9,505	10,738
2006.2	10,738	10,833
2006.3	10,833	12,212
2006.4	12,212	12,656
2007.1	12,656	13,180
2007.2	13,180	13,766
2007.3	13,766	14,450
2007.4	14,450	15,005
2008.1	15,005	14,358
2008.2	14,358	
2008.3		
2008.4		

Predicted NHUC using original number of house completion in **Australia**

	Two quarter lag	Three quarter lag
1987.1	41,416	46,607
1987.2	46,607	39,782
1987.3	39,782	49,904
1987.4	49,904	48,514
1988.1	48,514	62,687
1988.2	62,687	51,098
1988.3	51,098	63,790
1988.4	63,790	66,173
1989.1	66,173	71,246
1989.2	71,246	56,331
1989.3	56,331	53,782
1989.4	53,782	51,473
1990.1	51,473	54,468
1990.2	54,468	40,701
1990.3	40,701	45,982
1990.4	45,982	42,785
1991.1	42,785	45,585
1991.2	45,585	42,002
1991.3	42,002	44,259
1991.4	44,259	43,091
1992.1	43,091	53,986
1992.2	53,986	46,210
1992.3	46,210	48,476
1992.4	48,476	48,368
1993.1	48,368	56,156
1993.2	56,156	47,377
1993.3	47,377	48,144
1993.4	48,144	51,334
1994.1	51,334	59,292
1994.2	59,292	48,045
1994.3	48,045	49,200
1994.4	49,200	45,296
1995.1	45,296	45,361
1995.2	45,361	36,970
1995.3	36,970	36,367
1995.4	36,367	34,525
1996.1	34,525	36,800
1996.2	36,800	33,256
1996.3	33,256	35,132
1996.4	35,132	36,824
1997.1	36,824	41,620
1997.2	41,620	35,116
1997.3	35,116	42,672
1997.4	42,672	44,579
1998.1	44,579	44,017
1998.2	44,017	37,825
1998.3	37,825	46,244
1998.4	46,244	42,823
1999.1	42,823	50,929
1999.2	50,929	46,006
1999.3	46,006	59,087
1999.4	59,087	50,911
2000.1	50,911	51,128
2000.2	51,128	40,279
2000.3	40,279	40,544
2000.4	40,544	37,550
2001.1	37,550	42,433
2001.2	42,433	40,213
2001.3	40,213	49,385
2001.4	49,385	48,331
2002.1	48,331	59,340
2002.2	59,340	50,187
2002.3	50,187	54,605
2002.4	54,605	52,590
2003.1	52,590	58,709
2003.2	58,709	50,502
2003.3	50,502	62,702
2003.4	62,702	64,654
2004.1	64,654	60,251
2004.2	60,251	52,822
2004.3	52,822	64,771
2004.4	64,771	63,420
2005.1	63,420	67,101
2005.2	67,101	49,206
2005.3	49,206	57,340
2005.4	57,340	51,553
2006.1	51,553	64,218
2006.2	64,218	58,767
2006.3	58,767	66,641
2006.4	66,641	60,829
2007.1	60,829	66,012
2007.2	66,012	52,468
2007.3	52,468	62,932
2007.4	62,932	62,612
2008.1	62,612	73,071
2008.2	73,071	
2008.3		
2008.4		

Number of house completion moving average in **Australia**

	NHC moving average		NHC moving average
1987.1	20,344	**1998.1**	23,649
1987.2	21,223	**1998.2**	23,143
1987.3	21,985	**1998.3**	25,472
1987.4	23,283	**1998.4**	26,165
1988.1	22,841	**1999.1**	23,949
1988.2	23,093	**1999.2**	23,508
1988.3	25,750	**1999.3**	25,165
1988.4	29,688	**1999.4**	26,574
1989.1	29,176	**2000.1**	26,963
1989.2	28,096	**2000.2**	29,251
1989.3	31,345	**2000.3**	29,905
1989.4	32,672	**2000.4**	26,122
1990.1	29,931	**2001.1**	22,517
1990.2	26,261	**2001.2**	20,066
1990.3	25,623	**2001.3**	20,757
1990.4	26,337	**2001.4**	23,084
1991.1	24,639	**2002.1**	23,814
1991.2	22,568	**2002.2**	25,010
1991.3	23,738	**2002.3**	26,760
1991.4	25,401	**2002.4**	28,582
1992.1	25,202	**2003.1**	28,633
1992.2	24,526	**2003.2**	26,237
1992.3	26,138	**2003.3**	26,556
1992.4	29,487	**2003.4**	27,896
1993.1	29,537	**2004.1**	26,662
1993.2	28,140	**2004.2**	26,468
1993.3	29,947	**2004.3**	28,832
1993.4	32,411	**2004.4**	27,847
1994.1	30,903	**2005.1**	25,185
1994.2	28,711	**2005.2**	25,335
1994.3	30,470	**2005.3**	27,583
1994.4	33,522	**2005.4**	28,791
1995.1	31,852	**2006.1**	25,605
1995.2	27,482	**2006.2**	23,226
1995.3	26,796	**2006.3**	24,048
1995.4	26,439	**2006.4**	25,437
1996.1	23,633	**2007.1**	25,990
1996.2	20,966	**2007.2**	25,957
1996.3	20,758	**2007.3**	26,514
1996.4	21,475	**2007.4**	26,752
1997.1	20,835	**2008.1**	24,749
1997.2	20,388	**2008.2**	23,694
1997.3	22,063	**2008.3**	25,695
1997.4	24,237	**2008.4**	27,732

Predicted NHUC using number of house completion moving average in **Australia**

	Two quarter lag	Three quarter lag
1987.1	41,639	43,935
1987.2	43,935	43,306
1987.3	43,306	45,724
1987.4	45,724	47,508
1988.1	47,508	56,258
1988.2	56,258	58,993
1988.3	58,993	57,962
1988.4	57,962	65,291
1989.1	65,291	69,329
1989.2	69,329	64,141
1989.3	64,141	53,834
1989.4	53,834	52,732
1990.1	52,732	51,858
1990.2	51,858	46,395
1990.3	46,395	44,119
1990.4	44,119	42,396
1991.1	42,396	43,131
1991.2	43,131	44,934
1991.3	44,934	42,577
1991.4	42,577	42,056
1992.1	42,056	49,449
1992.2	49,449	50,774
1992.3	50,774	46,402
1992.4	46,402	47,496
1993.1	47,496	53,024
1993.2	53,024	53,277
1993.3	53,277	46,166
1993.4	46,166	50,457
1994.1	50,457	55,143
1994.2	55,143	55,327
1994.3	55,327	49,522
1994.4	49,522	46,170
1995.1	46,170	45,105
1995.2	45,105	42,256
1995.3	42,256	35,873
1995.4	35,873	35,372
1996.1	35,372	34,832
1996.2	34,832	36,503
1996.3	36,503	32,865
1996.4	32,865	36,381
1997.1	36,381	38,585
1997.2	38,585	39,257
1997.3	39,257	39,296
1997.4	39,296	43,990

	Two quarter lag	Three quarter lag
1998.1	43,990	43,433
1998.2	43,433	42,366
1998.3	42,366	42,408
1998.4	42,408	43,636
1999.1	43,636	47,567
1999.2	47,567	48,695
1999.3	48,695	52,330
1999.4	52,330	56,848
2000.1	56,848	52,452
2000.2	52,452	46,340
2000.3	46,340	39,570
2000.4	39,570	37,197
2001.1	37,197	38,850
2001.2	38,850	42,722
2001.3	42,722	44,743
2001.4	44,743	49,907
2002.1	49,907	54,276
2002.2	54,276	55,232
2002.3	55,232	54,152
2002.4	54,152	52,394
2003.1	52,394	56,209
2003.2	56,209	55,669
2003.3	55,669	57,727
2003.4	57,727	64,468
2004.1	64,468	62,655
2004.2	62,655	56,389
2004.3	56,389	60,601
2004.4	60,601	62,281
2005.1	62,281	65,500
2005.2	65,500	58,021
2005.3	58,021	53,838
2005.4	53,838	53,074
2006.1	53,074	59,369
2006.2	59,369	62,428
2006.3	62,428	63,022
2006.4	63,022	63,049
2007.1	63,049	63,242
2007.2	63,242	60,190
2007.3	60,190	57,765
2007.4	57,765	62,901
2008.1	62,901	67,804
2008.2	67,804	
2008.3		
2008.4		