Integrated urban system modelling: methodology and case study using multi-agent systems

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EXTENDED ABSTRACT

Challenges facing urban planners and governments continue to mount as populations in urban areas increase, pressure on the world's resources reaches critical levels and degradation of ecosystems around the world becomes increasingly apparent. The movement towards sustainable development has been met with enthusiasm by decision-makers, although exactly how to achieve this target, or even measure progress towards it, is not entirely evident. This paper explores how complex urban systems can be modelled holistically using a multi-agent based framework, and their sustainability assessed using a systems approach.

There are numerous subsystems and corresponding resources (natural, financial, human and man-made) within an urban development such as water, energy, transport, waste, economic and social systems. All of these subsystems and their interrelations can be modelled using multi-agent systems, along with effects of human behaviour, both spatially and temporally, in order to provide planners, developers and decision-makers with a better platform for understanding the complexities of the urban form.

As well as the presentation of a general overview of how the complexities of urban systems can be best captured using integrated modelling techniques such as multi-agent systems, the AUSTIME methodology, "Assessment of Urban Sustainability Through Integrated Modelling and Exploration", will be briefly presented. This methodology is designed to show how quantifiable sustainability assessment, based on system resource thresholds, and multi-agent based modelling, can be integrated into a framework that can be used for decision making and management relating to policy, regulation, planning, design and development of urban systems. The framework is designed to form part of a cyclic process, such as an adaptive management and learning or total quality management cycle that can explicitly include stakeholder participation and ongoing evaluation.

Specific examples of the implementation of this methodology are provided from a case study of Christie Walk, an eco-development in inner-city Adelaide, Australia. The case study involves the development of a prototype multi-agent based model coupled with a sustainability assessment framework that allows quantifiable sustainability comparisons for a range of indicators between the Christie Walk development and the larger Adelaide metropolitan area. Simulation results show that the eco-development performs significantly better than the majority of Adelaide metropolitan developments, specifically in carbon dioxide production, where the development's occupants rate below the 5th percentile of all Adelaide residents. The model is subsequently used to examine scenarios relating to changes in occupant behaviour, development infrastructure and location. Simulations comparing the relative impacts of car ownership and use behaviour, and infrastructure design changes (where air conditioners and heaters are required to regulate indoor temperatures), show that high in-house electricity use behaviour related to infrastructure changes to Christie Walk could have a greater effect on equivalent carbon dioxide production than increased car ownership and use (potentially due to a location change to an outer suburb of the Adelaide metropolitan area). This result is just one example that highlights the necessity for planners and governments to consider the relative importance and effects of all subsystems in urban areas on the overall system's sustainability before attempting to design and choose management options and plans.

It is envisaged that the AUSTIME methodology and case study application will help provide an example of how integrated modelling and sustainability assessment can be built into adaptive management cycles and effectively used as a decision making tool to work towards the sustainable development of urban environments and their inhabitants.

1. INTRODUCTION

Urban areas provide valuable services, opportunities for employment, social interactions and other recreational activities for their occupants, although owing to their dense populations and infrastructure, are also typically high resource users and waste producers. Planning, management and policy making for sustainable cities is thus not just about reducing the environmental impacts of cities on surrounding ecosystems, but also ensuring healthy economic growth, citizen satisfaction levels and adequate maintenance, development and redevelopment of infrastructure. In order to put into practice such management visions, a clear understanding of urban systems, their subsystems and interactions is required in order to gauge what effects specific policies or management plans will have on the sustainability of these systems. To allow this to occur, integrated urban modelling and integrated assessment techniques have been suggested as useful tools (Deakin et al. 2002). In recent years, a plethora of such tools and models with varying levels of integration has emerged to help analysis of urban systems at scales ranging from individual components of housing and infrastructure to the global level. A good overview of currently available tools can be found in Kapelan et al. (2005). Despite the large number of decision support tools and models in production, there are still relatively few that integrate water, waste, energy and socio-economic systems (especially at finer spatial scales, such as housing developments or suburbs). Tools with clear methods of assessing the sustainability of these systems relative to specific goals, under certain policy scenarios or different human behavioural patterns, are even rarer.

In order to address this apparent gap in decision support models and assessment methods for urban planning, policy, development and management, the AUSTIME methodological framework, "Assessment of Urban Systems Through Integrated Modelling and Exploration", was developed (Daniell et al., 2005). This paper will briefly outline this methodology, which couples systems analysis, sustainability assessment based on system thresholds and multi-agent simulation for scenario exploration, through its application to a prototype model and sustainability assessment of the Christie Walk eco-development in the city centre of Adelaide, Australia. It will particularly outline how urban subsystem models can be linked and how carefully selected sustainability indicators, such as equivalent carbon dioxide production, can be used to examine urban planning and policy priorities for sustainable development.

2. AUSTIME METHODOLOGY

The AUSTIME methodology, first outlined in Daniell et al. (2005), is presented in Figure 1. To explain the stages of the AUSTIME methodology in more detail, an example of its application to the Christie Walk eco-development in the Adelaide city centre will be used.

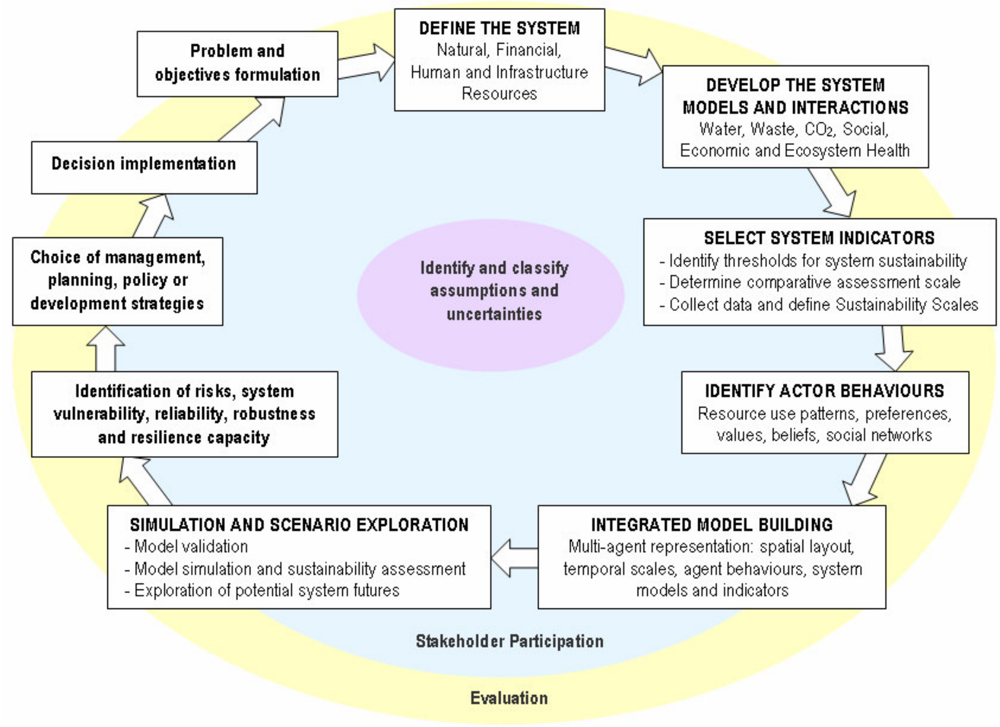

Figure 1. The AUSTIME methodology for housing developments

2.1. Case study application: Christie Walk

Stage 1: Problem formulation

Located in the south-west of the Central Business District of Adelaide in South Australia, Christie Walk is a medium density urban housing development comprised of 14 dwellings (straw-bale cottages, aerated concrete apartments and rammed earth construction town houses). The project is considered by many as a leading example of "sustainable development" due to several of its design features, which include: passive design of buildings to maximise energy savings; components of water sensitive urban design; an inner-city location in close proximity to services; and designated community spaces (Downton, 2002). However, substantiating these claims of sustainability linked to the development's design and location has proved difficult for the principal architect of the development, Paul Downton, due to the lack of an appropriate sustainability assessment methodology capable of quantifying sustainability relative to other urban developments and occupant behaviour. Consequently, the problem was formulated in order to quantify the overall sustainability of the Christie Walk development, relative to other developments in the larger metropolitan Adelaide area, followed by a critical analysis of which design elements and occupant behaviours lead to, or detract from, its level of sustainability.

Stage 2: Define the system

The first components of system definition for Christie Walk related to the system scale and analysis viewpoint. For the system scale, it was decided that the fence line of Christie Walk would be taken as the system boundary and that the assessment would be based on the interaction between occupant behaviour and the development's infrastructure (and resources entering and leaving the system from the start of occupant habitation). It is noted here that other viewpoints could have been taken, including that of investors or design and construction companies (potentially from earlier in the project's planning process), although these did not seem to meet the problem definition as well. Once the system scale and analysis viewpoint were determined, the system's resources: natural; human; financial; and man-made (infrastructure), as well as their flow, both within and to and from the system, were analysed based on Foley et al.'s (2003) systems approach. A diagrammatic version of this analysis is given in Daniell et al. (2005).

Stage 3: Develop system models and interactions

Following the AUSTIME methodology (Figure 1), the next step was to develop a set of subsystem models for Christie Walk that was representative of the system resources and flows outlined in Stage 2. Six interrelated models: water, carbon dioxide (CO_2), waste, economic, social and ecosystem health, encapsulated by occupant behavioural patterns, were developed. The models intrinsically included the Christie Walk system's infrastructure and are represented in Figure 2.

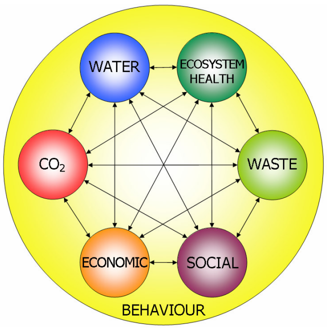

Figure 2. Framework for AUSTIME interrelated subsystem models

In general, the six conceptual models contain the following aspects, many of which are directly impacted upon by occupant behaviour:

- *CO_2 model*: embodied and operational energy use, calculated as an equivalent mass of CO_2, which incorporates the effects of building materials, infrastructure, biomass, electricity and gas use, as well as occupant transport use*;*
- *Water model*: all water related processes, including rainfall-runoff, infiltration, storage and potable and non-potable occupant water use;
- *Waste model*: all solid and liquid waste, both produced on site, and leaving the site, including: sewage; compost; waste to be recycled; and waste definitively disposed of to landfill;
- *Ecosystem Health model*: environmental aspects of the development, such as biodiversity, land use changes, pollution levels, air and water quality.
- *Economic model:* micro and macro economic processes for households such as income, expenditure, corresponding debt levels, taxes, charges, inflation, and interest rates; and the
- *Social model:* levels of occupant satisfaction relating to comfort, living conditions, access to services (transport, health, education, shopping), social networks, environmental quality, employment and governance structures, as well as equity amongst occupants.

Insufficient data were available for the development of an ecosystem health model for the case study considered. Consequently, it was omitted from the Christie Walk analysis. However, it is thought that the omission of this model would not impact the overall analysis too severely, primarily due to the fact that there was little to no perceived biodiversity on the site before construction (any improvements to this state will be shown in the next section to be sustainable, and therefore not quantified). In addition, some pollution, air and water quality effects could be partially taken into account in the social model.

There were also many linkages between each of the subsystem models, which are indispensable in any integrated modelling approach. Some of these linkages included: resource pricing affecting water, energy and transport use (CO_2 and water models); economic climate affecting household consumption and thus waste production; government policy (i.e. water restrictions) affecting resource use behaviour in the water, waste and CO_2 models; location, as well as housing development infrastructure and design (water, waste and CO_2 models), being related to the social model (in terms of well-being or occupant satisfaction with the current housing development situation); and embodied energy of the housing development's water and waste infrastructure being included in the CO_2 model.

Stage 4: Select system indicators

Following the conceptualisation and data collection for the subsystem models, one indicator significant to the sustainability of the overall development was chosen from each of the subsystem models. The selected indicators were: equivalent mass of CO_2 produced (CO_2 model); mains water use (water model); waste quantity sent to landfill (waste model); percentage use of available household debt (economic model); and an equitable satisfaction level (social model).

For each of these indicators, a threshold level between the ultimate sustainable state, and increasingly unsustainable states, needed to be defined, as well as a relative scale of comparison for the consequent construction of the Sustainability Scales, as outlined in Daniell et al. (2005). The Sustainability Scales Rating (SSR) distributions for each indicator at each time step, $x_i(t_j)$, are based on a conditional probability of exceedance of the ultimate sustainability threshold level of that resource, $threshold(x_{ij})$, of the population at the larger scale of comparison. The cumulative distribution SSR functions are calculated using Equation 1.

$$\mathrm{SSR} = 10\times \mathrm{F}(x_{ij}) = 10\times \mathrm{P}(\mathrm{X}\le x_{ij} \mid \mathrm{X} > threshold(x_{ij}))$$

$$= 10\times \int_{-\infty}^{x_{ij}} f(x_{ij} \mid x_{ij} > threshold(x_{ij}))dx_{ij} \qquad (1)$$

By coincidence, each of the five indicator threshold levels was set at 0. The scale of comparison used for the construction of the Sustainability Scales was chosen as the Adelaide metropolitan area. An example of one Sustainability Scale, for the CO_2 indicator of Christie Walk, is represented in Figure 3.

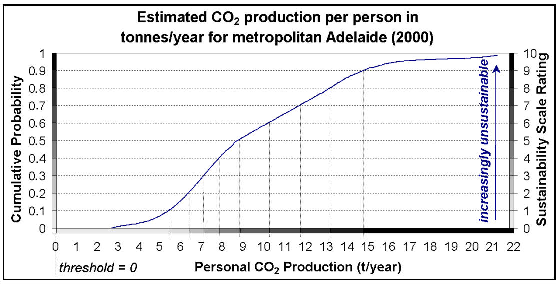

Figure 3. CO_2 Sustainability Scale

Taking an example from Figure 3, if occupants in Christie Walk produced 7 tonnes of equivalent CO_2 per person (through associated infrastructure, energy and transport use), they would be considered to be just under the 30th percentile of equivalent CO_2 production of the Adelaide metropolitan population, which would correspond to a 3 on the Sustainability Scale. This Sustainability Scale can be used to measure any indicator (providing sufficient and equivalent data are available at both spatial scales) and thus produces a uniform method of sustainability indicator assessment. For example, waste production can be measured against water use for equivalent levels of sustainability (or, more correctly, unsustainability) or the same indicators can be compared between developments in the same larger system.

Stage 5: Identify actor behaviours

The next stage of the AUSTIME methodology involved determining the behavioural patterns of the occupants at Christie Walk. This was carried out primarily using the following two methods: surveys of the residents and statistical methods of approximation from Census and other Adelaide services data. Due to a tight timeframe, the principal method of representing resident resource use behaviour was to divide Adelaide metropolitan area resource use distributions into three sections (low, moderate and high), and to then allocate the Christie Walk occupants to one of the three behavioural categories using the survey results and other data (i.e. electricity bills and water meter readings). Electricity use, in-house water use, total waste production, percentage waste diverted to recycling and travel distance were determined in this manner. An example of a divided distribution for total waste production is given in Figure 4. Other data relative to occupant preferences, values, beliefs, social networks and satisfaction levels (for input into the social model) were obtained from the survey results.

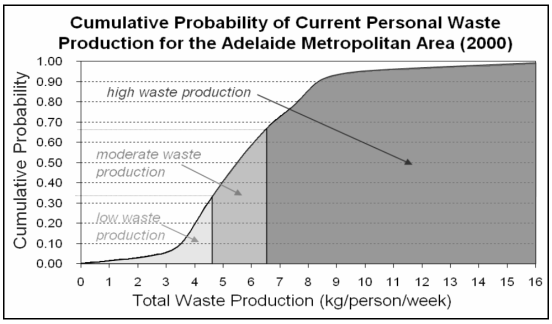

Figure 4. Waste production behavioural categories

Stage 6: Integrated model building

In order to combine all Christie Walk's interrelated subsystem models, indicators, occupant behaviours and spatial layout, multi-agent modelling, and more specifically the CORMAS platform (Bousquet et al., 1998), was used. In this platform, each dwelling (or "unit") from the architectural plan was represented as one cell of the spatial environment, as shown in Figure 5, and each household was programmed to be an "occupant" agent (represented in Figure 5 as pentagons in the units).

Figure 5. Christie Walk spatial layout: architectural plan and CORMAS model

Other environmental elements, such as the community garden, paths and car-park, were also programmed with their corresponding characteristics, and a "government" agent was created to be able to implement changes such as interest rate rises. Behavioural patterns were predominately programmed to randomly select from within the designated behavioural category of the Adelaide resource distribution (such as Figure 4). Certain elements of the subsystem model methods were run at the "household" level of the object oriented model (i.e. in-house resource use, household finances and the individual social sustainability models). Other elements were run at the main model or "development" level (such as rainfall-runoff, water storage levels, overall development resource usage and the Sustainability Scale Ratings for indicators).

The time-step of the multi-agent model was chosen as three months in order to observe seasonal difference in resource use behaviours and to improve computational efficiency. An exterior rainfall-runoff, tank storage and garden crop production model was created in Visual Basic at a daily time-step to observe the effects of historic rainfall data on the tank levels, overflow and required mains water top-ups, with 3 month relationships being calculated for input into the CORMAS model.

Stage 7: Simulation and scenario exploration

Following calibration, preliminary simulations and validation of the CORMAS model, using methods such as internal verification (refer to Daniell et al. (2005) for further details), the model was declared ready for use. Simulations were first run to assess the current and potential future sustainability of Christie Walk under a range of "business as usual scenarios" over a period of 30 years. One such scenario considering current levels of inflation (ranging between 2 and 4 percent), climatic conditions, behavioural resource use patterns and no new major technological innovations is shown in Figure 6.

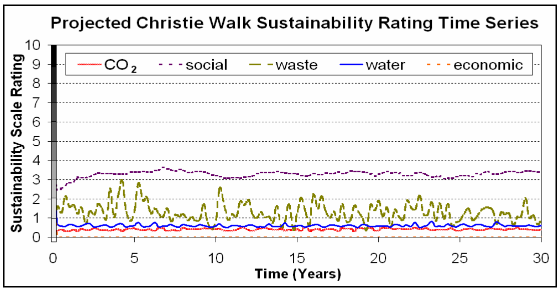

Figure 6. Christie Walk projected sustainability

The "base case" shown in Figure 6 shows that on the whole, Christie Walk is more sustainable than the majority of Adelaide metropolitan developments (SSR = 5 for an average Adelaide resident), especially in terms of mains water use and CO_2 production, where the occupants are well below the 10^{th} percentile of residents in the Adelaide metropolitan area.

In order to analyse the reasons behind these low sustainability scale ratings, as well as to determine potential risks, vulnerabilities and system robustness relative to sustainability of Christie Walk (Stage 8 of the AUSTIME methodology), further scenarios could be explored using the CORMAS model. The CORMAS Christie Walk model has previously been used to analyse the effects of drought on the water sensitive urban design components of the development (Daniell et al., 2004) and the effects of replacing the current Christie Walk residents with typically low, moderate and high level resource users (for in-house water use, electricity use, waste production and recycling) (Daniell et al., 2005). However, the magnitude of location, infrastructure, increased car ownership and use effects on CO_2

production and comparative Adelaide sustainability has yet to examined. The relative importance of each of these variables on Christie Walk's sustainability will therefore be explored in the next section.

3. SCENARIO RESULTS

The magnitude of equivalent CO_2 production components of Christie Walk was examined in a number of stages. At first, the effect of travel distance (based on Christie Walk car ownership levels) was analysed through scenarios with all occupants having high, moderate or low travel distances based on an estimated Adelaide distribution. The maximum difference exhibited throughout the simulation between the low and high distances was found to be a 1 SSR or a 10 percentile increase within the Adelaide population, as shown in Figure 7.

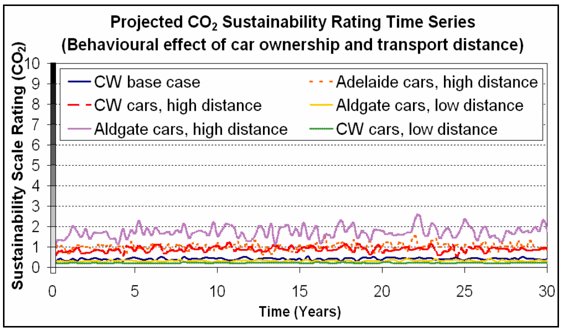

Figure 7. Car ownership and transport distance effects on Christie Walk's CO_2 sustainability

To analyse the effect of increased car ownership on the development's CO_2 sustainability, the number of cars in Christie Walk was increased to average Adelaide City levels and similarly run for high, moderate and low travel distances. In this scenario, it was observed that for the low travel distance simulation, there was little difference compared to Christie Walk sustainability levels. However, the high travel distance simulation exhibited an average 2 percentile increase over the Christie Walk car ownership levels, as shown in Figure 7. The effects of Christie Walk's location were also examined by effectively "moving" it to an outer suburb of Adelaide, where most services are generally located further away. For this scenario, car ownership levels were approximately increased to average Aldgate levels (a suburb in the Adelaide hills, approximately 15 km from the city centre) and simulations re-run for high, moderate and low travel distances, although it is noted that the average travel distances for such outer suburbs fall into the high category for Adelaide. The results from these simulations showed a 23 maximum percentile or 2.3 SSR difference between the high and low travel distances, with the high category falling into the 25 percentile category of Adelaide residents for CO_2 production, as shown in Figure 7.

The effect of occupant electricity use and infrastructure was then examined. The equivalent change relating to high and low occupant in-house electricity use at Christie Walk was found to be 0.8 SSR or an 8 percentile increase, as shown in Figure 8. To further test the effects of Christie Walk's infrastructure on limiting CO_2 production, a scenario was created where the infrastructure was effectively rebuilt with average Adelaide building materials that had approximately the same embodied energy levels as Christie Walk's materials, but which led to the need for a reverse cycle air-conditioner to moderate house temperatures. This scenario was calibrated with electricity data from the Mawson Lakes housing development (Oliphant, 2004), and then simulations were run for high, moderate and low electricity users. The 3.5 SSR increase for this infrastructure change between the high and low simulations is shown in Figure 8. Finally, the combined effect of location change (Aldgate car ownership levels and high travel distances) and infrastructure change is shown to reach the 60th percentile of the Adelaide population (Figure 8).

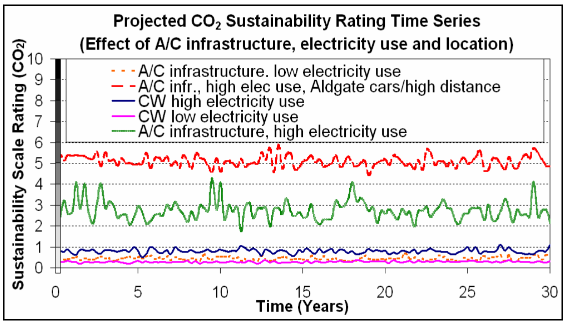

Figure 8. Location and infrastructure effects on Christie Walk's CO_2 sustainability

4. DISCUSSION

The results obtained indicate that there are many aspects of the Christie Walk development (specifically the infrastructure design, location, and the behaviours of relatively environmentally conscious residents) that lead to the development being significantly more sustainable than the large majority of developments in the Adelaide metropolitan area. This is particularly with respect to carbon dioxide production. It was also shown through scenario exploration that housing infrastructure, more specifically coupled with the need (or will) to use electric air-conditioners and heaters, is possibly the most significant factor that will lead to decreased levels of CO_2 sustainability (up to a 4 SSR increase, as opposed to a 2.3 SSR increase for changes to location and related higher travel distances and car ownership levels). For comparative interest, even if the Christie Walk infrastructure embodied energy doubled (for example if each unit was significantly increased in size), this would only contribute to an average 12 percentile increase in the CO_2 indicator if all other variables were unchanged.

Since some of these risks or factors that could compromise the CO_2 sustainability of Christie Walk, and eventually other developments in the Adelaide metropolitan area, have been identified, management plans could be designed and options chosen to improve some of these areas (Stage 9 of the AUSTIME methodology). Although not currently undertaken as part of this research due to the original problem formulation, the potential plans and their effects on not only the CO_2 sustainability indicator, but all indicators, could be reanalysed as part of an adaptive or total quality management cycle for other developments in the Adelaide metropolitan area, to help choose the options for the most promising overall sustainability improvements. Particularly important to re-examine is the social sustainability linked to these options, which will require further data collection, discussion and participation from Adelaide residents.

5. CONCLUSIONS

Appropriate management of any system, such as an urban housing development, requires knowledge relating to the system boundary, system resources, interactions between adjacent systems and allowable limits, or thresholds, for each resource, as well as the participation of the system's stakeholders and ongoing monitoring and evaluation. Integrated modelling and assessment nestled in a cycle, such as the AUSTIME methodology, can help to achieve this appropriate management, especially when the goal of this management is to achieve sustainable development. In order to know how and where to distribute limited planning and management resources (such as people, time and money), integrated models, such as the prototype model of Christie Walk outlined in this paper, can offer invaluable insights. Combining urban CO_2, water, waste, social and economic subsystem models, as well as occupant behaviour in a multi-agent model, many scenarios relating to changes in occupant behaviour, infrastructure and location were able to be simulated to provide insights into the reasons why the Christie Walk development is more sustainable than the majority of developments in the Adelaide metropolitan area. One result that could be further investigated by Adelaide planning authorities trying to lower the city's CO_2 production is the relative benefit of reducing air conditioning and heating use (commonly relating not only to the design and infrastructure of homes, but to occupant behaviour), as opposed to reducing car use. Learning to consider the relative importance and effects of all subsystems in urban areas on overall system sustainability through the application of integrated frameworks, such as AUSTIME, should aid the decision-making and sustainable management processes of our urban environments.

6. ACKNOWLEDGMENTS

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