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EXTRACTION AND ANALYSIS METHODOLOGY FOR SUPPORTING COMPLEX SUSTAINABLE DESIGN

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ABSTRACT
The advent of computer-based tools in design has meant ever larger sets of parameters can be taken into consideration. It also means other factors associated with environmental issues can be considered and increasingly there are legislative requirements to do so. This means increasing demands are placed on designers to create high quality, innovative, sustainable solutions to satisfy many stakeholders. Design by nature is a complex interdisciplinary practice. Managing complexities requires the support of specifically created tools and methods to handle a large number of design parameters. This is particularly true of the built environment where such parameters include the spread of buildings, energy consumption, handling of waste, management of water and transport needs. The paper discusses a methodology that seeks to support the decision making process and design optimization for complex designs, demonstrating an approach for dealing with integrated assessments and optimal design choices. It is based upon automatically studying relations between design parameters so that interdependencies can be obtained, related parameters can be clustered and sensitivities established.

Keywords: sustainability, built environment, model extraction, sensitivity analysis, design optimization

1 INTRODUCTION
In the current climate, the issues surrounding sustainable design are those which many disciplines are responding to with increasing vigor. Sustainable design is complex. It demands a holistic approach and necessitates decision making and strategy integration at a very early stage of the design process. It also demands compliance with details at a micro level. An abstract approach cannot be undertaken especially in the circumstances with data that is inherently highly contextual and highly integrated. The design process becomes reliant on the explicit contribution of data provided by designers with specialist expertise which is fully comprehensive in terms of data aggregation. Increasingly, the demand on detailed data is becoming more evident as part of the earlier stages within the design process.
The last decade has seen an increase in design tools, supporting methodologies and frameworks for sustainable design that are used as part of a business need for companies to be environmentally responsible. While there are guidelines for assessment methods and policy development, there is little readily available instruction on managing the actual complexities and sheer volume of detail at a complex level. An example, particularly apt, can be found within the built environment sector where current practice does not always have easy access to appropriately integrated analytical tools to inform sustainable decision making for projects at all scales [1].
Existing tools, both qualitative and quantitative, are in many cases dependent upon the knowledge base of the user. For this sector, but also design in general, there is often an emphasis on tools that are more quantitative in order to support design decisions and achieve measurable design targets. Within a multidisciplinary network, the stakeholders other than the clients themselves include the specialists that provide and formulate the data within the design process.

1.1 Sustainable Design for the Built Environment
For the built environment, the contribution to sustainable development has a large impact as buildings, through their operational greenhouse gas emissions, account for one third of the energy demand in Europe [2]. In fact, there is increasing effort to research sustainable development methods and push the boundaries of science and engineering applications in order to drastically reduce energy consumption and greenhouse gas emissions in general.

Professionals within the planning and built environment sector are constantly required by the defining nature of sustainability to consider and satisfy the demands of a wide range of stakeholders. Design within this sector requires the expertise of many specialist disciplines and it has been proposed as being 'the most multidisciplinary practice in all of the design professions' [3]. Within the built environment, the issues of sustainable design compound the complexities within the discipline of masterplanning.

1.2 Built Environment Masterplanning

Masterplanning in a non-statutory sense is the process which can be interpreted as the entire program of activities within a particular project. Such activities include integrated service provisions ranging from the preparation, conceptual design and detailed design through to the construction and use of a built environment.

Masterplanning and the development of masterplans, are heavily reliant upon the expertise of designers and the technical specialists from various disciplines who may use a combination of tools and methods to support their own data capture for different design scenarios.

Integrated assessments are used to actively monitor and evaluate the interactions and integration of multidisciplinary data capture. They not only give an instantaneous measure of how sustainable a scenario may be, they also form part of a natural optimization method through iterative design and analysis. In essence, each iteration increases the designer's incremental knowledge of the design problem and contributes towards an eventual optimized design proposal.

A key stage in any design optimization activity is to understand the influencing factors that may have varying effects, large or small, on a design. Such factors, which may be considered as design variables, have different levels of sensitivity that contribute to the overall design. Examining the sensitivity of design variables is considered as an important activity in any optimization process and has its place in good design practice. Sensitivity analysis of such variables is considered an important activity in such design and has therefore formed a key part of the research reported here.

Section 2 discusses integrated resource management (IRM), an integrated assessment tool and approach increasingly used in current masterplanning activity. Section 3 provides a design strategy created on the foundations of IRM methodology. This involves the extraction and sensitivity analysis of design variables as key process activities. Section 4 gives an industry case study as an example of the applied methodology and the last section provides an evaluation and concluding remarks.

2 INTEGRATED RESOURCE MANAGEMENT

Integrated resource management (IRM) is an emerging design support tool that has the capability to support design, planning and decision making on a complex level such as urban masterplanning which runs alongside sustainability appraisal and assessment methods [4]. IRM itself has its roots and main associations within the management of natural resources such as water.

2.1 Masterplanning Design and Assessment Frameworks for IRM

Within masterplanning, sustainability assessment frameworks are created and increasingly legislated in order to support effective sustainable design. These design and assessment frameworks often make use of metrics or performance indicators in order to assess, compare and guide improvement of design proposals and design solutions [5]. Since masterplanning is a multidisciplinary activity, many disciplines will contribute their own data to the metrics and performance indicators that are developed within such frameworks. These are also often considered as a fundamental preceding activity in the development of IRM tools.

The key motivation for an IRM tool is to aggregate information from the different technical design streams into one common data model for easier accessibility and assessment. As a standalone tool, this then enables the different disciplines to produce an augmented but more importantly an integrated set of metrics for assessing masterplans for a built environment. For illustration, an assessment framework and accompanying IRM model for the masterplan of an urban development may consider, contain and represent data obtained from several disciplines. These may include those that specialize in carbon and environmental footprinting, energy strategists, water management, the handling of waste, transportation requirements, materials used in construction, the social mix of communities, and the quantity and mix of landuse.

Owing to the nature of masterplanning, there is a constant challenge between the different disciplines involved to integrate their individual design strategies. Designers and planners must consistently acknowledge and resolve the issues or conflicts that occur when accounting for complex interrelationships between design parameters of different disciplines and resource streams. In such a multidisciplinary activity this has previously been difficult to do. Such complex and increasingly numerous interrelations of design inputs often lack transparency and there often exists a complex cascade of data effects, thus pointing to the need for better data management and modeling tools [1, 6].

2.2 IRM Models

An IRM model developed by engineering and design consultancy firm Arup, as a quantitative urban metabolism tool for use in eco-city masterplanning, is considered and adapted for study. The model and tool itself, allows neighborhood, city or regional plans and policies to be developed and prioritized in the context of the relevant integrated resource streams [1]. Figure 1 shows a generic example of some common inputs and outputs, and some of the technical disciplines that provide captured data along with examples of graphical outputs. Key data and metrics used within any typical IRM model forms a mass of design input variables which can be interpreted via many different outputs. Any specific outputs may be interpreted as a key performance indicator (KPI) in which a KPI's value can be treated as a design parameter and therefore forms one or part of the overall design objectives.

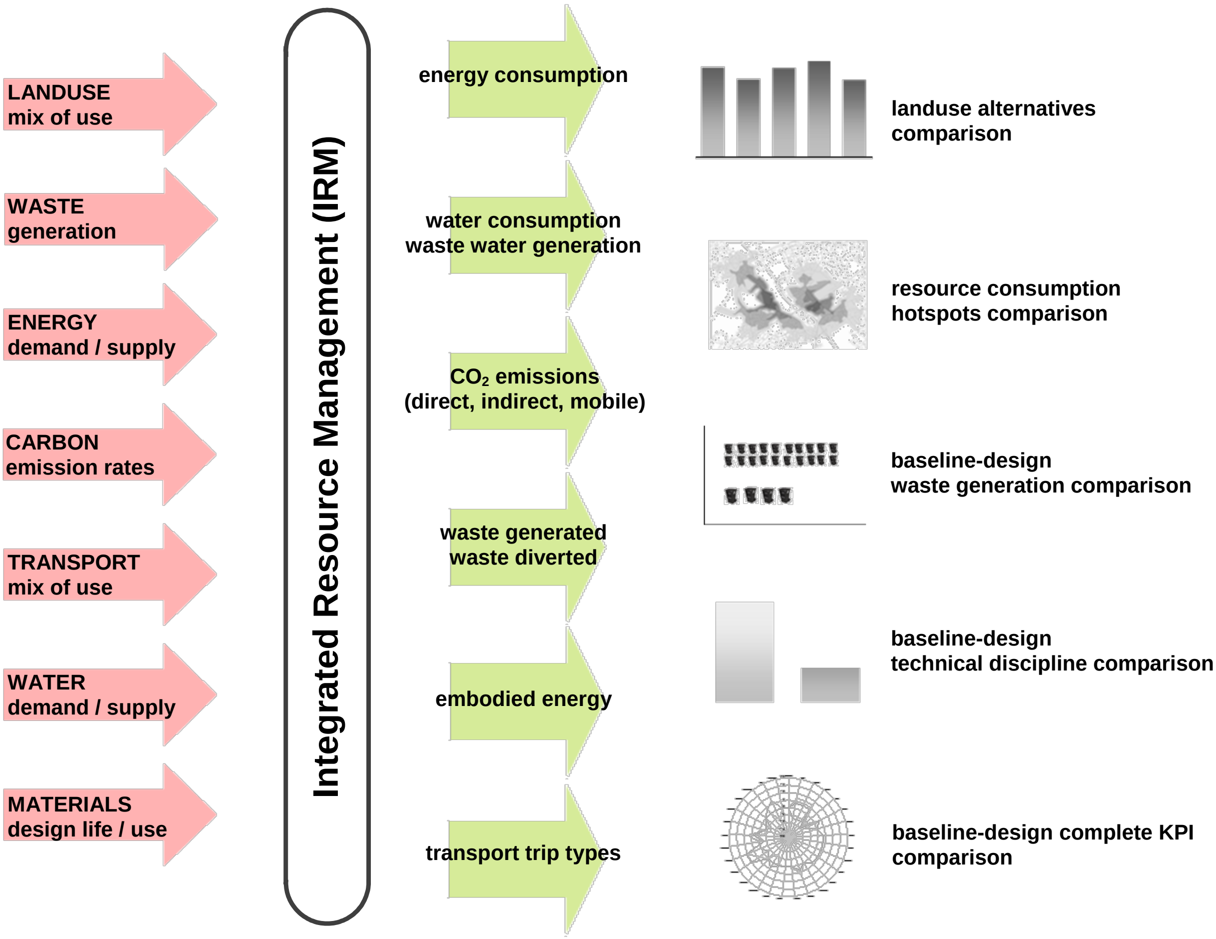

Figure 1. An Overview of the IRM Data Flows within a Model [1]

In general, many design activities and created models evaluate and provide the necessary integrated assessments for design scenarios and strategies. These evaluations are based on the declared objectives and parameters which are interpreted, in many cases, through a series of calculations using both captured data and databases of information. A large number of associated variables (in the order of thousands) are handled within such a process.

IRM models are in commercial use due to their capabilities to explore synergies, feedback loops and trade-offs for different design proposals. Since complexities exist within the relationships of the many design variables, there also exists a need to efficiently manage the large volume of data in order to produce optimum strategies and scenarios for masterplan options. This can be done using extraction of model data and sensitivity analysis which forms the foundation activities of the created methodology discussed in the next section.

3 EXTRACTION AND ANALYSIS METHODOLOGY FOR DESIGN SUPPORT

A methodology to support the use of IRM models and the decision making process for masterplanning built environments is now described. It is intended that this methodology exist alongside current supporting models and has the capability to become an integral part of sustainability assessments and other associated appraisals.

Within this, the extraction and analysis methodology (EAM) has been created with the aspiration of enabling designers or, more specifically in this paper, the planners within the built environment to better understand and manage the complexity within their assessment models. It also enables a more efficient and focused approach to design and optimization. The methodology and the defining activities are summarized in Figure 2 and explored in the following sections.

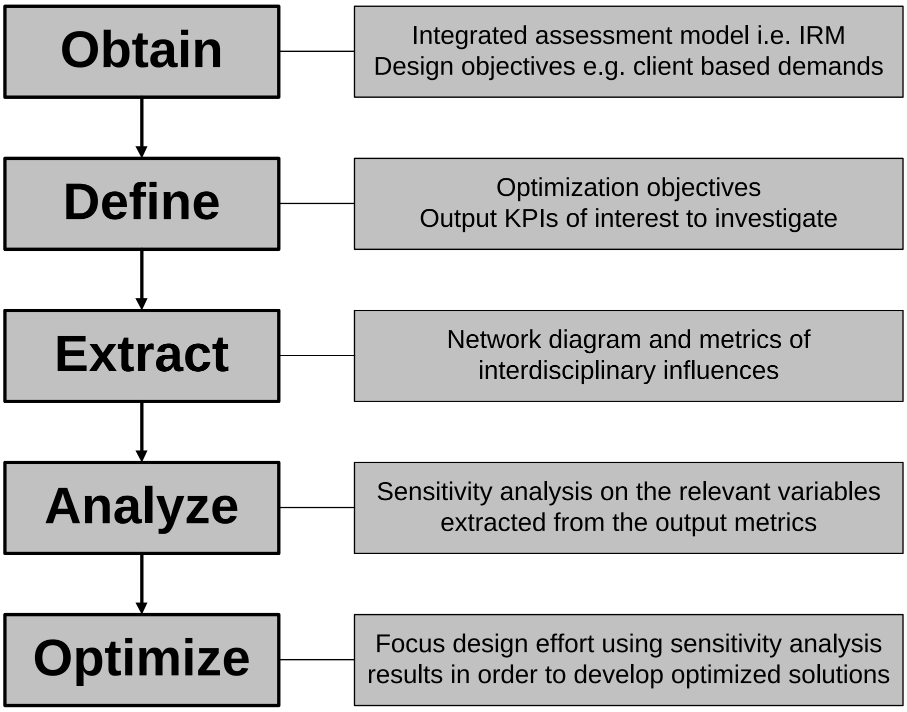

Figure 2. Extraction and Analysis Methodology (EAM) Overview

3.1 ‘Obtain’ and ‘Define’

In many disciplines, some form of integrated assessment model is created in order to evaluate particular aspects for a design or part thereof. These may be potential solutions, different cases or scenarios and initial conditions or design boundaries. Such models are then used as part of solution search and discovery and design optimization. This activity of integrated assessment has become the foundation of the methodology. IRM models are an example of an integrated assessment tool created to assess and develop masterplan strategies and scenarios for implementation. Such a model holds a large volume of highly integrated and complex data.

Obtaining an assessment model, necessary data and the key design objectives falls under the activities of ‘obtain’ and ‘define’. In the early stages of the methodology, it is important to explicitly confirm either the optimization objectives and/or the output KPIs of interest in order to correctly focus the activities within the latter stages of the process. In fact, the majority of which, are commonly defined and described within the accompanying design and assessment framework generally laid out in the early stages of design effort.

In the case of the research reported here, a complete assessment model was obtained and adapted as part of an industry case study. However, it is conceivable that an assessment model may be created as opposed to obtained. The stages of 'extract' and 'analyze' which are discussed further in the following sections contribute to the 'optimize' activity which allows the 'facilitator' of EAM to focus their design effort or optimization with confidence.

3.2 'Extract'

The aim of extraction within the methodology is to disseminate understanding of specific aspects of an assessment model relevant to a specific optimization objective, output KPI or general area of interest. At the same time, this enables data handling at a more manageable level. From the assessment model, the output KPI then has its formula extracted, i.e. the path of its calculation. The extraction tool evaluates the interaction of every variable contributing to the output being investigated. The connections between all variables can then be displayed graphically as a network diagram using a custom viewer, developed for the GraphML format, in many different layout forms which each has its own benefit depending on what is required. Using the custom viewer allows insight into the complexity in terms of the sheer volume of variables, their context, and the detail of their interconnections.

The tool developed for the extraction activity not only provides an interactive and instantaneous means for visually investigating the scope of interconnections between variables across boundaries of different disciplines, there is also a series of metrics that are calculated. These metrics have been built into the extraction tool in order to further contribute to the advantages of design illumination and focus of design effort discussed further in Section 3.3. The extraction metrics are listed below.

- **Variable count and distribution** – metrics that detail the total variables contributing to the KPI under investigation and the distribution of variables with respect to the disciplines of their origin. It also details the variables that are most frequently used in any calculation paths.
- **Independent variable count and distribution** – metrics that detail the total independent variables and the distribution of these with respect to the disciplines of their origin. Such variables are explicitly not obtained from calculations within the assessment model itself and are strictly inputs only. The most frequently used independent variables are also reported.
- **Reference count and distribution** – metrics that detail the total connections made between variables and the average number of references made with respect to the disciplines of their origin within the assessment model.

The counts and distributions for variables, independent variables and references provide insight into the complexity of the assessment model and the distribution of data. This is not only with respect to the KPI in question but also to the disciplines involved. For example, it is possible to look at the distribution and origin of variables that extend from the mix of landuse and how they might interact and effect water management, handling waste and energy strategy solutions.

In addition to these evaluated metrics, the connections between different disciplines are examined and detailed through a summary matrix which provides insights into interdisciplinary influences and how they interact. Three different summaries can be provided.

- **A direct reference matrix** – this details the references made between each variable from one discipline and all other relevant disciplines. This demonstrates the disciplines that are connected and the frequency of such connections.
- **An independent direct reference matrix** – this details the references only made between each independent variable from one discipline and all other relevant disciplines. This demonstrates the disciplines that are connected and the frequency for independent variables only.
- **An indirect reference matrix** – this details the indirect references made between each variable from one discipline and all other relevant disciplines. This demonstrates the extent of variable interaction, potential locations for effects of changes and the complexity within the entire model.

The next stage of the methodology uses a sensitivity analysis tool. Although the extraction and the metrics provide key insights and valuable information to widen the knowledge base of the planners, the sensitivity analysis requires only information based on the independent variables.

3.3 'Analyze'

Sensitivity analysis is an activity employed in numerous mathematical and scientific fields and has significant benefits in interpreting and managing large and complex data networks. For the built environment, sensitivity analysis can reduce the corresponding volume of data and design effort for 'robust assessments of impact' [7].

The primary function of such an analysis is to determine how a model's specific output responds to changes to input variables. It is therefore possible to determine which variables hold more dominance when interpreted as design parameters and ultimately their contribution to one or more design objectives. Carried out as a series of experimental runs, variables are altered under specific conditions. The design of such sets of experimental runs relates to the area of Design of Experiments (DoE) [8].

There exist numerous types of experimental design which vary in efficiency and the insight provided when investigating the sensitivity of a model. These can be grouped under two main approaches. In the first instance, single variance analysis involves the variation of an individual variable for evaluation against a single output. In the second instance, multiple variance analysis involves the variations of several variables for evaluation against one or more outputs. This paper deals with multiple variance analysis.

Sensitivity analysis itself carries a certain amount of subjective influence dependent on the chosen methodology applied and the explicit data values specified to populate a model. Within complex models such as the IRM, boundaries and limitations exist which are often only tacitly understood. These must be acknowledged and interpreted for sensitivity analysis in terms of upper and lower limits of variation that can be described as confidence intervals [9].

Regardless of the design of experiment, sensitivity analysis provides scope for design space exploration and scenario or solution refinement contributing to good general design methodology. There are four key advantages to carrying out a sensitivity analysis.

- **Designer illumination** – sensitivity analysis has the ability to show both variable dominance and interaction. This indicates which outputs are most sensitive and the variables that affect this change. Continuous analyses on design iterations also increase the knowledge of overall responsiveness of outputs to the input variables.
- **Reducing the problem space** – in assessing which variables have more or less dominance, it is possible to narrow the scope of the problem space. Certain assumptions may be tested and this may regard variables as being entirely ineffective or effective within a model. It can also demonstrate potential conflicts between variables and outputs.
- **Focusing design effort** – the results of the sensitivity analysis provide the designer with increased knowledge of the potential design solution space and contributing factors. Hence, it allows the designer to focus efforts on specific areas of relevant interest and the variables that have the biggest scope for effect.
- **Design optimization** – sensitivity analysis contributes to an optimization process for design in general and also provides scope for multi-objective optimization. It is possible to look at specific variable effects on not one but many aspects of specific design objectives simultaneously. This increases knowledge not only of variable behaviour but also of outputs within the system.

Due care must be taken when carrying out a sensitivity analysis especially when there exist interactions between a large number of variables. These interactions are not always immediately obvious when considering the inputs and outputs that are part of an applied sensitivity analysis. For example, consider the space occupied by a certain shape with the basic input variables of height, width and depth. The output of volume is sensitive to these variables individually but in reality the output is far more sensitive to their interactions, which are some multiplication of the three variables together. When considering a large number of variables, there is an explosion in the number of interactions to consider which means that carrying out a full sensitivity analysis may be prohibitively time consuming and computationally expensive. This is especially the case with an IRM model that contains thousands of variables alongside several tens of output KPIs. Ideally, each combination of design variables, along with every possible interaction, should be tested against the relevant design objective. This process is an example of experimental design known as a factorial design. There exist many techniques which carry out sensitivity analysis and handle the complexities that occur in factorial design.

The computational cost of analysing many more than ten variables, as with IRM, means such analysis begins to become increasingly intractable. For this reason, more efficient designs have been developed such as PB designs [10]. First reported by Plackett and Burman, PB designs are among the computationally least expensive but lack insight into the interactions between variables. The method has linearity in the number of experimental runs compared to the number of variables, this makes a PB design relatively inexpensive in terms of the computational effort [10,11]. The main usage of PB design is when the number of variables under consideration or the duration of each experiment (i.e. the number of analysis runs) means that the primary consideration in design choice is computational efficiency. This is the case and reason why PB design has been applied alongside the IRM model in the research reported here as a large number of variables are being considered and managed.
The extraction tool actually has the capability to run without any real data since it simply extracts the relationships and/or calculations established in the model for processing input data. However, the sensitivity analysis tool developed from PB design techniques explicitly requires an integrated assessment model with real data inputs. During the analysis, the tool is constantly reading and writing values into the assessment model in order to test for the sensitivity of the variables. The independent variable count and distribution metrics directly prescribe the input variables for analysis. There are three prerequisites required for setting up each of the variables investigated.

- **An interpreted description** for each variable so that it is fully comprehensive with respect to the project as certain variables may exist only as a series of shorthand expressions.
- **A specified default value** that is relevant and realistic. This value may be zero, estimated, or an initial value depending on the purpose of the sensitivity analysis and the user experience.
- **A specified confidence interval** bounding each variable with a high or low value. This may be expressed either as a percentage of the specified default value or numerically.

The interpreted description and specified default value is in most cases, directly obtained from the assessment model. Due care must be taken when bounding each variable with its confidence interval as the sensitivity analysis is most effective and yields the best results when its variables can be investigated over their widest possible range. Setting the interval may require knowledge and experience specific to a technical stream or discipline. It also involves a certain level of intuition and tacit knowledge in order to set the correct realistic context for the sensitivity analysis.
The result of the sensitivity analysis is a list of variables tested and ordered according to which the output (KPI) is most sensitive to changes in. The absolute values in this list are numeric and normalised within the tool for interpretation and then rated on a scale from zero to one-hundred. In the sensitivity tool itself, a variable that has high dominance has a value of one-hundred where as a variable with zero dominance has a value of zero.
When examining the results of the sensitivity analysis, the general shape of the list indicates whether certain variables have dominance on the output under investigation. There may be variables that have substantial dominance individually or as a group of variables. It is important to note that beyond a certain point in the list, all variables have similar sensitivity values. At this occurrence, it is not sensible to interpret the figures since their effects are not significant enough to be able to differentiate them from potential aliasing effects.
Following the sensitivity analysis, the designer gains valuable insight into the most dominant variables within a design set and/or scenario, the user of the tools and overall methodology can take the results in order to demonstrate those variables that have the most dominance in the overall design solution so that design iterations may be focused on varying those that are most influential. It also sets the scope for awareness of design constraints and design compromise since variables that may be more dominant to one variable may have less influence on another when considering a different output KPI.

3.3 'Optimize'

Over the course of a design process, the output KPIs are effectively used as optimization goals within the design and planning process. Where an assessment model such as IRM is in use, it is possible to define an optimization problem in such a way that inputs from many different disciplines may be varied so as to optimize the output KPIs calculated by the assessment model. Using this approach, KPIs established in the initial stages of the process may be interpreted as design constraints [12] and general optimization techniques such as direct search and gradient methods [13] may be applied.

Design improvement and optimization in masterplanning within the built environment sector is essentially a process that is often heavily reliant upon designer intuition as precedent-based design [5]. Whilst different scenarios are set up with changes in variables, it is the result of each iteration that provides illumination for the design decisions made in order to reach potential design solutions so that undesirable designs or scenarios are slowly funnelled out.

The extraction and analysis methodology has the capability to support a wide range of decision support tools and provides the initial setup for optimization. The 'optimize' activity is used to automatically adjust the relevant variables for a design solution.

4 INDUSTRY CASE STUDY

Using the created extraction and analysis methodology (EAM), the tools and techniques were applied to a case study which considers an eco-city masterplanning development for the scenario of a highly populated urban area of 7,500,000 square meters. An IRM model was developed for the study which modeled a series of KPIs and provided an integrated assessment of a design scenario based on inputs from several technical disciplines. As a performance indicator, the KPI representing carbon emissions was selected as that of interest in this study. The results are presented in the following tables.

Table 1. Extraction metrics

Metric Details / Description	**Count**	**Percentage Distribution of Metric Data (%)**					**Most frequently used variable**
		landuse	transport	water	energy	other	
Variable count / distribution	2357	2	30	16	40	12	1. energy demand 2. water demand
Independent count / distribution	1117	2	25	17	41	15	1. energy demand 2. residential land
Reference count / distribution	3404	3	8	5	17	N /A	N /A

Table 1 shows the results of the extraction on the variables within the case study model. These represent a selection of the results for four key disciplines of landuse mix, transportation, water management, and energy consumption. All other disciplines are grouped into the last section for percentage distributions of the variables.

Table 2. Reference Matrix of Direct Variable References

Percentage Distribution of Direct References (%) (3404)	from\to	landuse	transport	energy	water
	landuse	0.5	0	2	0.4
	transport	0	29	2	0
	energy	0	0	37	0
	water	0	0	0.1	16

Table 3. Reference Matrix of Independent Direct Variable References

Percentage Distribution of Independent References (%) (1516)	from\to	landuse	transport	energy	water
	landuse	8	0	1	4
	transport	0	24	2	0
	energy	0	0	25	0
	water	0	0	0	12

Table 4. Reference Matrix of Indirect Variable References

Percentage Distribution of Indirect References (%) (41,068,458)	from\to	landuse	transport	energy	water
	landuse	< 0.01	0	1	< 0.01
	transport	0	< 0.01	0.4	0
	energy	0	0	28	0
	water	0	0	10	< 0.01

Table 2 demonstrates the percentage distribution of the total number of references made from one discipline to another directly, whilst Table 3 demonstrates the same distribution for independent variables. Table 4 demonstrates the distribution of the total number of references made from one discipline to another indirectly. The total number of references is listed in the left hand column of each reference matrix and the same disciplines are reported as in Table 1.

The results from the extraction indicate that energy as a discipline contributes the largest number of variables towards the KPI of carbon emissions. The ‘energy demand’ variable from this discipline is also most referred to within the assessment model as well as being the most frequently used in calculating an assessment for total carbon emissions. The frequency of the ‘water demand’ variable in total variables and ‘residential land’ variable in total independent variables also demonstrates that these are particularly involved in calculations for carbon emissions. In addition, demonstrating the total number of references may be considered as a direct correlation to the complexity that is handled within each discipline for the specific output KPI of carbon emissions. It also demonstrates the capability of the IRM model to efficiently manage a large number of interlinked and complex variables in order to support design decision making.

From the generated extraction metrics, the list of independent variables was carried forward for use with the sensitivity analysis tool. Alongside the distribution of variables and the most frequently used variable, the sensitivity analysis provided a perspective on the variables that hold the most dominance. Table 5 provides an indication for the percentage of variables that have a very high, moderate and low dominance with respect to the disciplines previously detailed. These results then provided a design focus in which those variables that demonstrated a high dominance were examined more closely in an effort to optimize the KPI for carbon emissions and further understand their influence.

Table 5. Sensitivity Analysis Distribution of Dominance

Technical Discipline	**Distribution of Variable Dominance (%)**		
	High	**Moderate**	**Low**
landuse	17	41	42
transport	2	68	30
energy	12	62	26
water	4	81	15

4.1 Translational Applications

The approach presented is within the scope of the built environment for architecture, engineering and construction industry but the tools and methods may be applied in general design activity and transferable to different design themes. Overall, the aim of the extraction and analysis methodology is to gain an understanding of design variables, the parameters, and their relationships to specified objectives. This understanding then seeks to guide the designer to an optimized scenario in which decision support is made. Since bespoke assessment models can be easily created for the variables of any product and/or system design and, the other tools used in the methodology are established, it is conceivable that translational application exists.

5 CONCLUDING REMARKS

The tools developed within the methodology of extraction and analysis (EAM) provide a set of metrics for an approach that commercially uses IRM as an integrated assessment tool complemented by an assessment framework. These metrics clearly demonstrate the complexity held within such IRM models but also provide insight into the interdisciplinary nature of the design variables demonstrating the extent of interacting disciplines. This insight allows optimization and indeed general design solutions of certain objectives to become more manageable. Design in the built environment involves the demand, on designers and planners, to consider an ever increasing and large number of design variables that must satisfy the many design objectives and stakeholders. In masterplanning, design is both a multidisciplinary and interdisciplinary practice and managing complex data from several technical streams is difficult. The EAM and its associated tools proposed and reported in this paper provide support for the use of IRM in masterplanning. The key contribution of this work is the ability of the method and tools to transparently demonstrate and manage the complexities and interdependencies within integrated data to direct design focus for complex sustainable design.

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