Chapter 3

Computational Model of a Generative Design Agent

To achieve dynamic designs of virtual worlds, this study applies a computational approach using rational design agents. Chapter 3 presents a Generative Design Agent (GDA) model. The computational processes of the GDA model are specifically developed for reasoning and designing in virtual worlds. Each GDA has the following two main features:

- Reasoning mechanism: a GDA is able to monitor the virtual world and various activities that occur in the world, interpret the occupants' needs in the virtual world and the state of the world based on these observations, hypothesise design goals in order to satisfy these needs, and finally design and implement virtual environments or initiate other changes in the world according to the goals on behalf of the occupants.
- Design component: a GDA is a design agent. The GDA's design component is supported by the application of a generative design grammar. The concepts and development of generative design grammars are introduced in Chapter 4.

Each GDA is associated with a virtual world occupant and serves as his/her personal design agent to dynamically design virtual worlds as needed. Section 3.1 introduces the GDA model, with progressive diagrams that show the development of the GDA model and its relation to other agent models. Section 3.2 discusses the representations of virtual worlds. These representations are then used in section 3.3 to illustrate the computational processes of the GDA model. The five computational processes of the GDA model are sensation, interpretation, hypothesising, designing and action. Section 3.4 further analyses the GDA model in terms of a design model. Section 3.5 concludes the chapter with a discussion that highlights the advantages and differences of applying the GDA model for dynamic designs of virtual worlds.

3.1 GENERATIVE DESIGN AGENT MODEL

The GDA model is a rational agent model. As reviewed in Chapter 2 section 2.3, a rational agent is situated in an environment, is capable of reasoning about the environment, and acts upon its beliefs and desires (Wooldridge 2000). This definition distinguishes rational agents from computational agents that perform actions based on predefined events, such as search agents on the web. We consider some of the existing rational agent models as the basis for developing the GDA model.

Russell and Norvig's reflex agent diagram (2003) illustrates the basic concepts of a rational agent (Figure 2.15 on p21). The agent reasons about the condition of its environment and acts based on condition-action rules. Russell and Norvig's utility agent diagram (2003) illustrates a rational agent with additional beliefs and more complex reasoning processes (Figure 2.16 on p21). For the development of the GDA model, we draw attention to how Russell and Norvig's models define basic relations between an agent and its environment and provide mechanisms for establishing such relations.

Maher and Gero (2003, 2002) develop a common agent model for 3D virtual worlds (Figure 2.17 on p22). Using this model, each virtual world component can be represented as an agent element, and a virtual world can be represented by a society of agents; for example, wall agents, door agents, room agents or building agents. Each agent is able to sense and respond to its use in the virtual world by reasoning about the current state of the virtual world.

In this common agent model, key agent components and computational processes are outlined, for supporting interactions between the agents and the virtual world, and interactions among different agents in the virtual world. As shown in Figure 3.1, an agent developed using this common model has five kinds of reasoning: sensation, perception, conception, hypothesizer and action. Using such a reasoning mechanism, agents are able to behave in three different modes: reflexive, reactive and reflective, each mode requires more complex reasoning.

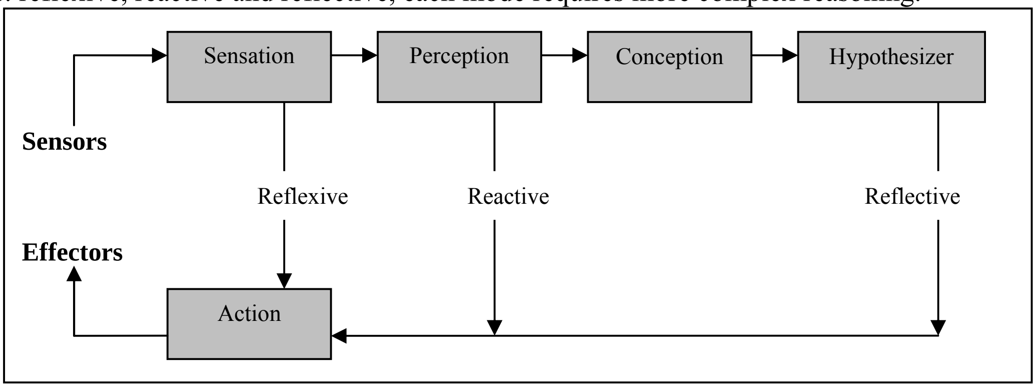


Figure 3.1 (identical to Figure 2.18 on page 23) A common agent model for 3D virtual worlds (after Maher and Gero 2003, 2002).

In contrast to this common agent model for 3D virtual worlds, the GDA model takes a different approach by giving the agencies to the virtual world occupants, rather than to the virtual world components that make up the environments. Using the GDA model, a virtual world can also be represented by a society of GDAs. Each GDA is associated with a virtual world occupant and serves as his/her personal design agent in the virtual world. Because the agencies are given to the occupants, rather than to existing virtual world components, the virtual world therefore does not need to be pre-defined. GDAs reason, design and act on behalf of the virtual world occupants, and dynamically design, implement and manipulate the virtual world during the use of the world.

The reasoning mechanism of the GDA model is developed based on the framework shown in Figure 3.1, where sensors and effectors act as the interface between a GDA and the virtual world. The five computational processes of the GDA model are sensation, interpretation, hypothesising, designing and action. They are illustrated in Figure 3.2. More details of these processes are discussed in section 3.3. Compared to Maher and Gero’s common agent model for 3D virtual worlds, the differences of the GDA model may be briefly outlined thus:

- Sensation: similarly, a GDA uses its sensors to retrieve relevant raw data from the virtual world to prepare for the process of interpretation.
- Interpretation: in the common agent model, an agent interprets the sense data internally in two different stages via the processes of perception and conception. The common agents develop very complex internal design representations in terms of percepts and concepts. For the purpose of designing virtual worlds in this research, the GDA model does not require such complex levels of reasoning in interpreting virtual worlds. Therefore the original processes of perception and conception are integrated into the processes of

interpretation in the GDA model. The GDA conducts interpretation in three different stages. The ultimate outcomes of the processes are the GDA's interpretations of the occupants' current needs and the current state of the virtual world. The processes of interpretation are elaborated in section 3.3.1.

- Hypothesising: in the process of hypothesising, the GDA sets up design goals that aim to eliminate or reduce the mismatches between the current needs of the occupants and the current state of the virtual world.
- Designing: the GDA model is also a design agent model. GDAs are developed specifically for the purpose of designing virtual worlds. To address this design aspect, one of the computational processes of the GDA model is singled out as designing. In the process of designing, the GDA provides a virtual world design in order to satisfy its current design goals that are related to designing virtual worlds for the moment. The design component of the GDA is supported by the application of a generative design grammar. More details of designing are discussed in section 3.3.3.
- Action: the final processes of action include action planning and action activation. The GDA plans actions for implementing the generated virtual world design and realising other initiated changes, and activates these actions in the virtual world. The results of action lead to changes in the virtual world, which trigger the GDA to start a new cycle of reasoning and designing. In this manner, the virtual world is able to be dynamically designed, implemented and manipulated, when it is needed.

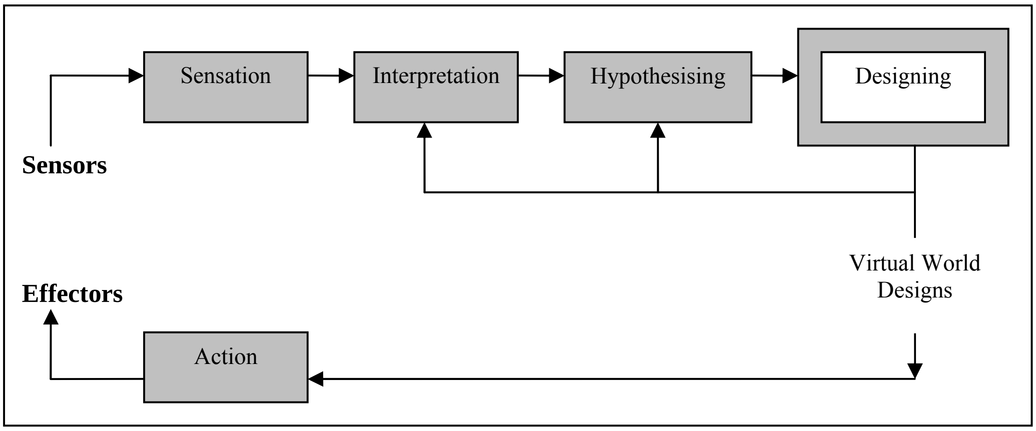


Figure 3.2. Five computational processes of the GDA model.

3.2 REPRESENTATIONS OF A VIRTUAL WORLD

According to Gero and Kannengiesser (2004), a situated view assumes a non-static environment where the act of designing takes place. Adopting such a view, the process of designing in the GDA model can be modelled as the interactions of three representations of the environment: the external world, the interpreted world and the expected world. The external world comprises representations outside a designer. The interpreted world is the internal representation of the external world that exists inside the designer, in terms of his/her knowledge and experience. The expected world is a part of the interpreted world in which the results of designing are predicted based on the designer's current design goals and his/her interpretations of the current state of the world. Figure 3.3 illustrates the interactions among these three representations.

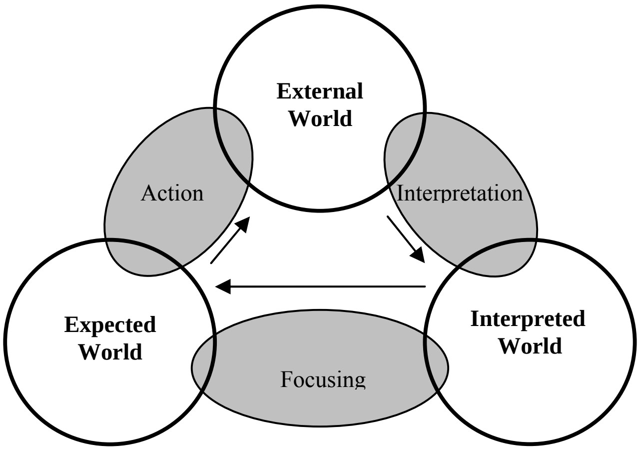


Figure 3.3. Interactions among the external world, the interpreted world and the expected world (after Gero and Kannengiesser 2004).

3.2.1 Three Views of a Virtual World

The development of the GDA model adopts the notions of the above three representations for the context of designing virtual worlds in order to capture the characteristics of dynamic, non-static virtual worlds. For GDAs, a virtual world W can be viewed as the union of the external world W_{ext}, the interpreted world W_{int}, and the expected world W_{exp}.

$$W = W_{ext} \cup W_{int} \cup W_{exp} \quad (3.1)$$

At any given moment, a virtual world comprises various components that construct the environments, the representations of its occupants, and events occurred in the world. These entities exist outside a GDA. Depending on the GDA's capability and focus, the external world W_{ext} of the GDA can include the whole or parts of these entities. The interpreted world W_{int} is the GDA's internal representation of W_{ext}, which reflects the GDA's interpretations of W_{ext}. The occupants' current needs in the virtual world and the current state of the virtual world are interpreted in W_{int}. The expected world W_{exp} is where the GDA hypothesises its design goals and generates virtual world designs, or initiates other changes in the virtual world for satisfying the goals. The GDA's design goals are hypothesised by matching against its interpretations of the occupants' current needs and the current state of the virtual world. A virtual world design is then generated to satisfy the current design goals that are related to designing virtual worlds by applying the GDA's generative design grammar.

The external world W_{ext} comprises A_{ext}, E_{ext}, wA_{ext} and O_{ext}.

$$W_{ext} = A_{ext} \cup E_{ext} \cup wA_{ext} \cup O_{ext} \quad (3.2)$$

where A_{ext}, E_{ext} and O_{ext} are each represented by a set of elements of the same kind, and wA_{ext} is represented by an ordered list of properties.

$A_{ext} = \{occupant_{ext\_1}, occupant_{ext\_2}, ..., occupant_{ext\_n}\}$

$E_{ext} = \{event_{ext\_1}, event_{ext\_2}, ..., event_{ext\_n}\}$

$wA_{ext} = (size_{ext}, capacity_{ext}, owner_{ext}, 3D\_object\_library_{ext}, system\_time_{ext},)$

$O_{ext} = \{O_{ext\_1}, O_{ext\_2}, ..., O_{ext\_n}\}$

Symbol A_{ext} is the representation of the virtual world occupants, that is, GDAs, and avatars (occupants who have no agencies in the virtual world).

Symbol E_{ext} represents various events in the virtual world.

Symbol wA_{ext} represents the attributes of the virtual world; for example, size, capacity and owner of the virtual world, 3D object library, system time of the virtual world and so on.

Symbol O_{ext} represents objects in the virtual world. In an object-oriented virtual world, an object may refer to a virtual place; for example, a virtual gallery or a virtual meeting room. An object may also refer to an entity in a virtual place, or it can form a part of the place; for example, a digital picture in a virtual gallery, or a wall of the virtual meeting room.

The interpreted world W_{int} comprises A_{int}, E_{int}, wA_{int} and O_{int}.

$$W_{int} = A_{int} \cup E_{int} \cup wA_{int} \cup O_{int} \quad (3.3)$$

where A_{int}, E_{int}, wA_{int} and O_{int} are the GDA's internal transformations of A_{ext}, E_{ext}, wA_{ext} and O_{ext}:

$A_{int} = \tau(A_{ext})$

$E_{int} = \tau(E_{ext})$

$wA_{int} = \tau(wA_{ext})$

$O_{int} = \tau(O_{ext})$

Symbol A_{int}, E_{int}, wA_{int} and O_{int} represents the GDA's interpretations of A_{ext}, E_{ext}, wA_{ext} and O_{ext}. Further, the GDA interprets the current needs of the virtual world occupants N and the current state of the virtual world sT:

$N = \tau(W_{int})$

$sT \in W_{int}$

The expected world W_{exp} comprises A_{exp}, E_{exp} and O_{exp}

$$W_{exp} = A_{exp} \cup E_{exp} \cup O_{exp} \quad (3.4)$$

where A_{exp}, E_{exp} and O_{exp} are used to represent design goals hypothesised by the GDA that aim at eliminating or reducing the mismatches between N and sT:

$A_{exp} \in \tau_A(N, sT)$

$E_{exp} \in \tau_E(N, sT)$

$O_{exp} \in \tau_O(N, sT)$

Symbol A_{exp} represents the expected attributes of the GDAs or the avatars; for example, the expected location of a GDA or an avatar.

Symbol E_{exp} represents the expected events in the virtual world; for example, to send a message to all the occupants who connect to the virtual world.

Symbol O_{exp} represents the expected objects and their attributes in the virtual world.

The GDA's expected world does not include wA_{exp}, as the attributes of the virtual world are generally not changeable.

3.2.2 Virtual World Objects

This study adopts the Function-Behaviour-Structure (F-B-S) framework (Gero 1990) to the context of designing virtual worlds for representing virtual world objects. In general:

$$O_i = O_i^F \cup O_i^B \cup O_i^S \quad (3.5)$$

where O_i represents any virtual world object.

For the GDA model, the representation of a virtual world object in the external world includes structures $O_{ext\_i}^S$. Functions $O_{ext\_i}^F$ and behaviours $O_{ext\_i}^B$ of the object are assumed nil, and are addressed in the GDA's interpreted world.

$O_{ext\_i}^S = \{structure_{ext\_1}, structure_{ext\_2}, ..., structure_{ext\_n}\}$

$O_{ext\_i}^B = \emptyset$

$O_{ext\_i}^F = \emptyset$

Every object in the interpreted world has a counterpart in the external world. The interpreted functions $O_{int\_i}^F$ and behaviours $O_{int\_i}^B$ are derived from the interpreted structures $O_{int\_i}^S$.

$O_{int\_i}^S = \tau(O_{ext\_i}^S)$

$O_{int\_i}^B = \tau(O_{int\_i}^S)$

$O_{int\_i}^F = \tau(O_{int\_i}^B)$

An object in the GDA's expected world may or may not have a counterpart in the interpreted world, since a virtual world design can either be generated based on existing structures or by new creations. The GDA's design goals that are related to designing virtual worlds are hypothesised in terms of the expected functions $O_{exp\_i}^F$ and the expected behaviours $O_{exp\_i}^B$, both according to the current needs of the virtual world occupants N and to the current state of the virtual world sT.

$$O_{exp\_i}^F \in \tau(N, sT)$$
$$O_{exp\_i}^B = \tau(O_{exp\_i}^F)$$

Once a design goal that is related to designing virtual worlds is hypothesised, the GDA applies its generative design grammar to generate structures represented by $O_{exp\_i}^S$, to be realised in the virtual world, in order to satisfy the design goal or parts of the design goal.

$$O_{exp\_i}^S = \tau(O_{exp\_i}^F, O_{exp\_i}^B) \quad (3.6)$$

In summary:

- The external world $W_{ext} = A_{ext} \cup E_{ext} \cup wA_{ext} \cup O_{ext}$. The representation of each virtual world object in the external world includes structures $O_{ext\_i}^S$. Functions $O_{ext\_i}^F$ and behaviours $O_{ext\_i}^B$ of the object are assumed nil, and are addressed in the GDA's interpreted world.
- The GDA's interpreted world $W_{int} = A_{int} \cup E_{int} \cup wA_{int} \cup O_{int}$. Each object in the interpreted world has a counterpart in the external world. $O_{int\_i}^S$ can be the same or different from $O_{ext\_i}^S$ depending on the individual GDAs. $O_{int\_i}^F$ and $O_{int\_i}^B$ are derived from $O_{int\_i}^S$.
- The GDA's expected world $W_{exp} = A_{exp} \cup E_{exp} \cup O_{exp}$. An object in the expected world may or may not have a counterpart in the interpreted world. $O_{exp\_i}^F$ and $O_{exp\_i}^B$ represent a GDA's design goals that are related to designing virtual worlds. To satisfy these design goals or parts of these goals, the GDA applies its generative design grammar to generate a virtual world design or parts of the design represented by $O_{exp\_i}^S$ for the moment to be implemented in the virtual world.

3.3 COMPUTATIONAL PROCESSES OF THE GENERATIVE DESIGN AGENT MODEL

Using the above representations, the five computational processes of the GDA model can be defined as below. Figure 3.4 illustrates these processes.

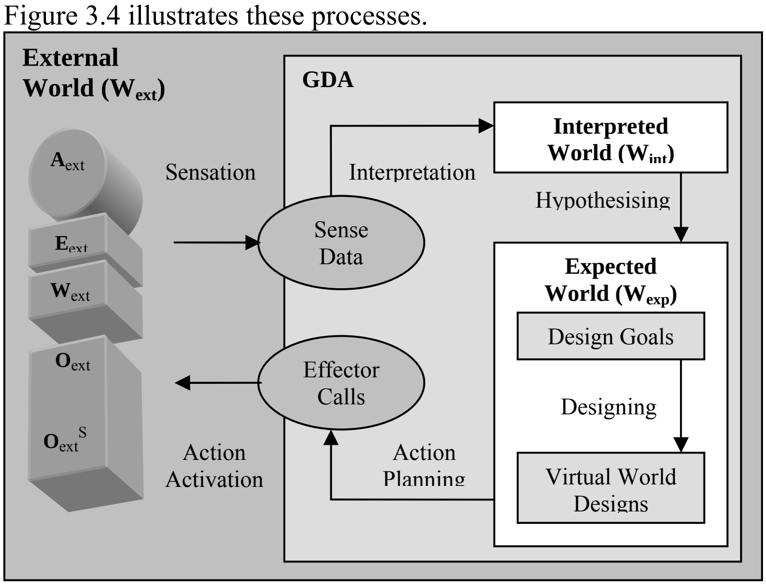


Figure 3.4. Five computational processes of the GDA model.

In the process of sensation, a GDA retrieves relevant raw data from the external world to prepare for the processes of interpretation.

In the process of interpretation, the raw sense data are filtered, focused and transformed to construct the GDA's interpreted world W_{int}:

$$W_{ext} \rightarrow W_{int} \quad (3.7)$$

$$W_{ext} = A_{ext} \cup E_{ext} \cup wA_{ext} \cup O_{ext} \quad (3.2)$$

$$W_{int} = A_{int} \cup E_{int} \cup wA_{int} \cup O_{int} \quad (3.3)$$

More importantly, the GDA further interprets the current needs of the virtual world occupants N and the current state of the virtual world sT.

$$N = \tau(W_{int})$$

$$sT \in W_{int}$$

In hypothesising, the GDA sets up design goals in its expected world W_{exp} to eliminate or reduce the mismatches between N and sT:

$$W_{int} \rightarrow W_{exp} \quad (3.8)$$

$$W_{exp} = A_{exp} \cup E_{exp} \cup O_{exp} \quad (3.4)$$

There can be at least three different types of design goals hypothesised by the GDA. The first type of design goal is related to designing virtual worlds, which is the focus of this study. These design goals are represented by expected functions $O_{exp}{}^{F}$ and expected behaviours $O_{exp}{}^{B}$:

$$O_{exp}{}^{F} = \{O_{exp\_1}{}^{F}, O_{exp\_2}{}^{F}, \ldots , O_{exp\_n}{}^{F}\} \quad (3.9)$$

$$O_{exp}{}^{B} = \{O_{exp\_1}{}^{B}, O_{exp\_2}{}^{B}, \ldots , O_{exp\_n}{}^{B}\} \quad (3.10)$$

for any expected function $O_{exp\_i}{}^{F}$ and expected behaviour $O_{exp\_i}{}^{B}$:

$$O_{exp\_i}{}^{F} \in \tau(N, sT)$$

$$O_{exp\_i}{}^{B} = \tau(O_{exp\_i}{}^{F})$$

Sometimes, to eliminate or reduce the mismatches between N and sT requires not only virtual world designs, but also other changes in the virtual world. The second type of design goal involves initiating changes of attributes to the GDAs or the avatars in the virtual world: A_{exp}. The third type of design goal involves initiating events that occur in the virtual world: E_{exp}.

$$A_{exp} \in \tau_{A}(N, sT)$$

$$E_{exp} \in \tau_{E}(N, sT)$$

In designing, the GDA applies its generative design grammar to generate a virtual world design for the moment in order to satisfy the current design goals that are related to designing virtual worlds. The design is represented by expected structures $O_{exp}{}^{S}$:

$$O_{exp}{}^{S} = \{O_{exp\_1}{}^{S}, O_{exp\_2}{}^{S}, \ldots , O_{exp\_n}{}^{S}\} \quad (3.11)$$

where any expected structure $O_{exp\_i}{}^{S} = \tau(O_{exp\_i}{}^{F}, O_{exp\_i}{}^{B})$.

The processes of action include action planning and action activation. The GDA first plans actions for implementing the generated virtual world design: $O_{exp}{}^{S}$, and for realising other initiated changes: A_{exp} and E_{exp}. Next, these planned actions are activated via the GDA's effectors in the virtual world:

$$O_{exp}{}^{S} \rightarrow O_{ext}{}^{S} \quad (3.12)$$

$$A_{exp} \rightarrow A_{ext} \quad (3.13)$$

$$E_{exp} \rightarrow E_{ext} \quad (3.14)$$

The process of sensation is rather straight forward. Interpretation, hypothesising, designing and action are further elaborated and illustrated in sections 3.3.1, 3.3.2 and 3.3.3. These five computational processes form a recursive loop. New creations and changes of the virtual world will trigger the GDAs to start a new cycle of reasoning and designing. In this manner, virtual worlds are able to be dynamically designed, implemented and manipulated as needed specifically for the moment.

3.3.1 Interpretation

Interpretation has three separated processes. They are marked as 1, 2 and 3 in Figure 3.5. The GDA's interpreted world W_{int} is constructed based on the external world W_{ext}:

$$W_{ext} \rightarrow W_{int} \quad (3.7)$$

$$W_{ext} = A_{ext} \cup E_{ext} \cup wA_{ext} \cup O_{ext} \quad (3.2)$$

$$W_{int} = A_{int} \cup E_{int} \cup wA_{int} \cup O_{int} \quad (3.3)$$

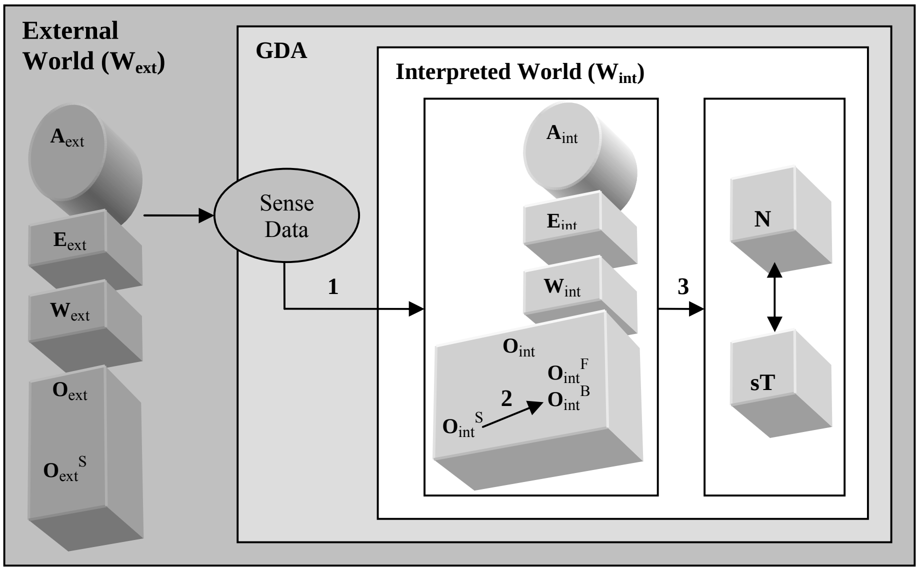


Figure 3.5. Three processes of interpretation.

In the first process of interpretation, the sense data from the external world W_{ext} are filtered, focused and transformed into information that are relevant and can be understood by the GDA:

$$A_{int} = \tau(A_{ext})$$

$$E_{int} = \tau(E_{ext})$$

$$wA_{int} = \tau(wA_{ext})$$

$$O_{int\_i}^S = \tau(O_{ext\_i}^S)$$

In the second process of interpretation, for any virtual world object, the interpreted functions $O_{int\_i}^F$ and interpreted behaviours $O_{int\_i}^B$ are derived from the interpreted structures $O_{int\_i}^S$.

$$O_{int\_i}^B = \tau(O_{int\_i}^S)$$

$$O_{int\_i}^F = \tau(O_{int\_i}^B)$$

In the final process of interpretation, the current needs of the virtual world occupants N, and the current state of the virtual world sT, are interpreted based on the information gained from the first two processes:

$$N = \tau(W_{int})$$

$$sT \in W_{int}$$

To support each computational process, a GDA's reasoning mechanism is developed as a general rule base, where each rule can be expressed using the formula of "IF… THEN…". In the processes of interpretation, the following formulas are applied to develop rules for interpreting A_{int}, E_{int}, wA_{int}, $O_{int\_i}^S$, $O_{int\_i}^B$, $O_{int\_i}^F$, N and sT. Symbol C used in the formulas represents certain general conditions. To demonstrate the uses of these formulas, each formula is presented with an example rule.

Formula 1: IF A_{ext} AND C ($C \in W_{ext}$) THEN A_{int}	Example rule: IF GDA Acosta is sensed in the virtual world. AND Acosta is set as the artist character in the virtual gallery. THEN It is interpreted that the artist is present in the virtual world.
Formula 2: IF E_{ext} AND C ($C \in W_{ext}$) THEN E_{int}	Example rule: IF An object is mouse-clicked by the artist. THEN It is interpreted that the artist is examining the object.
Formula 3: IF wA_{ext} AND C ($C \in W_{ext}$) THEN wA_{int}	Example rule: IF The system time of the virtual world is between 6pm to 6am. THEN It is interpreted as "night" time in the virtual world.
Formula 4: IF $O_{ext\_i}^{S}$ AND C ($C \in W_{ext}$) THEN $O_{int\_i}^{S}$	Example rule: IF An object is configured with script "create picture". THEN The structure of the object is interpreted as having a programming component for rendering digital images.
Formula 5: IF $O_{int\_i}^{S}$ AND C ($C \in W_{ext}$) THEN $O_{int\_i}^{B}$	Example rule: IF The structure of an object is interpreted as having: 1. A visual component of a 3D model with a flat surface. 2. A programming component for rendering digital images. THEN The behaviour of the object is interpreted so as to display digital images.
Formula 6: IF $O_{int\_i}^{B}$ AND C ($C \in W_{ext}$) THEN $O_{int\_i}^{F}$	Example rule: IF The behaviour of the object is interpreted so as to display digital images. THEN The function of the object is interpreted as a digital picture frame.
Formula 7: IF W_{int} THEN N	Example rule: IF The artist is present in the virtual world. AND The artist has one exhibition to display. AND Visitors are present in the virtual world.

	THEN A gallery area is needed for displaying the exhibition.
Formula 8: IF W_{int} THEN sT	Example rule: IF No gallery area is recognised in the virtual world. THEN The current state of the virtual world is interpreted as having no exhibition space available.

3.3.2 Hypothesising

In the process of hypothesising, the GDA establishes design goals in its expected world W_{exp} in order to eliminate or reduce the mismatches between the occupants' current needs (N) and the current state of the virtual world (sT). The process of hypothesising is illustrated in Figure 3.6.

$$W_{int} \rightarrow W_{exp} \quad (3.8)$$

$$W_{exp} = A_{exp} \cup E_{exp} \cup O_{exp} \quad (3.4)$$

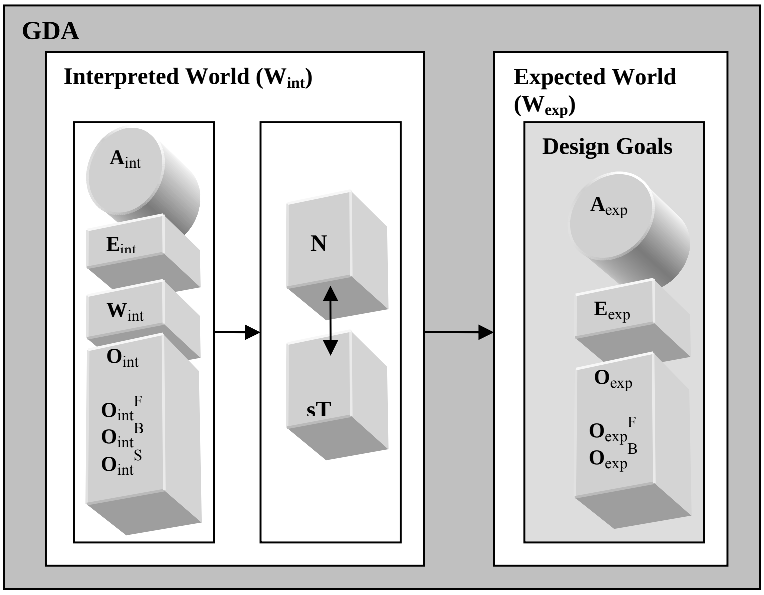


Figure 3.6. The process of hypothesising.

An object in the GDA's expected world may or may not have a counterpart in the interpreted world, since a virtual world design can be generated based either on existing structures or by new creations. There can be at least three different types of design goals hypothesised by the GDA. The first type of design goal is related to designing virtual worlds. These goals are represented by expected functions O_{exp}^F and expected behaviours O_{exp}^B:

$$O_{exp}^F = \{O_{exp\_1}^F, O_{exp\_2}^F, \dots , O_{exp\_n}^F\} \quad (3.9)$$

$$O_{exp}^B = \{O_{exp\_1}^B, O_{exp\_2}^B, \dots , O_{exp\_n}^B\} \quad (3.10)$$

for any expected function $O_{exp\_i}^F$ and expected behaviour $O_{exp\_i}^B$:

$$O_{exp\_i}^F \in \tau(N, sT)$$

$$O_{exp\_i}^B = \tau(O_{exp\_i}^F)$$

The second type of design goal involves initiating changes of attributes to the GDAs or the avatars in the virtual world: A_{exp}; for example, to change the location of a GDA or an avatar. The third type of design goals involves initiating events in the virtual world: E_{exp}; for example, to send a message to all the occupants who connect to the virtual world.

$A_{exp} \in \tau_A(N, sT)$

$E_{exp} \in \tau_E(N, sT)$

In the processes of hypothesising, the following formulas are applied to develop rules for hypothesising O_{exp}^F, O_{exp}^B, A_{exp}, and E_{exp}. Symbol C used in the formulas represents certain general conditions. To demonstrate the uses of these formulas, each formula is presented with an example rule.

Formula 9: IF N AND sT THEN O_{exp}^F	Example rule: IF A gallery area is needed for displaying an exhibition. AND The current state of the virtual world is interpreted as having no exhibition space available. THEN The expected function is a gallery area in the virtual world for displaying the exhibition.
Formula 10: IF O_{exp}^F AND C ($C \in W_{ext}$) THEN O_{exp}^B	Example rule: IF The expected function is to provide a gallery area in the virtual world for displaying an exhibition. AND The exhibition contains twenty digital images. THEN The expected behaviour of the gallery area (to be generated) is to display twenty digital images.
Formula 11: IF N AND sT THEN A_{exp}	Example rule: IF A visitor is invited to an exhibition. AND The current state of the virtual world is interpreted as: 1. The exhibition is displayed in a gallery area located at (x, y, z). 2. The visitor is outside the visual boundary of the gallery area. THEN The expected location of the visitor is set to (x, y, z).
Formula 12: IF N AND sT THEN E_{exp}	Example rule: IF A gallery area is needed for displaying an exhibition. AND The current state of the virtual world is interpreted as that a gallery area is available at location (x, y, z). THEN Send a message to inform the artist about the gallery area.

3.3.3 Designing and Action

In the process of designing, a GDA generates a virtual world design for the moment to satisfy its current goals that are related to designing virtual worlds. The virtual world design is represented as O_{exp}^{S}:

$$O_{exp}^{S} = \tau(O_{exp}^{F}, O_{exp}^{B}) \quad (3.6)$$

The process of designing requires the GDA to have generative power for providing virtual world designs as needed. The design component of the GDA is supported by the application of a generative design grammar. Driven by the GDA's design goals that are related to designing virtual worlds, the GDA applies its generative design grammar to generate a virtual world design, in order to satisfy the relevant design goals or parts of the goals.

The process of designing is followed by the process of action, which includes action planning and action activation. The GDA first plans actions for implementing the generated virtual world design, O_{exp}^{S}, and for realising other initiated changes, A_{exp} and E_{exp}. Next, these planned actions are activated via the GDA's effectors in the virtual world. Figure 3.7 illustrates the process of designing and the process of action.

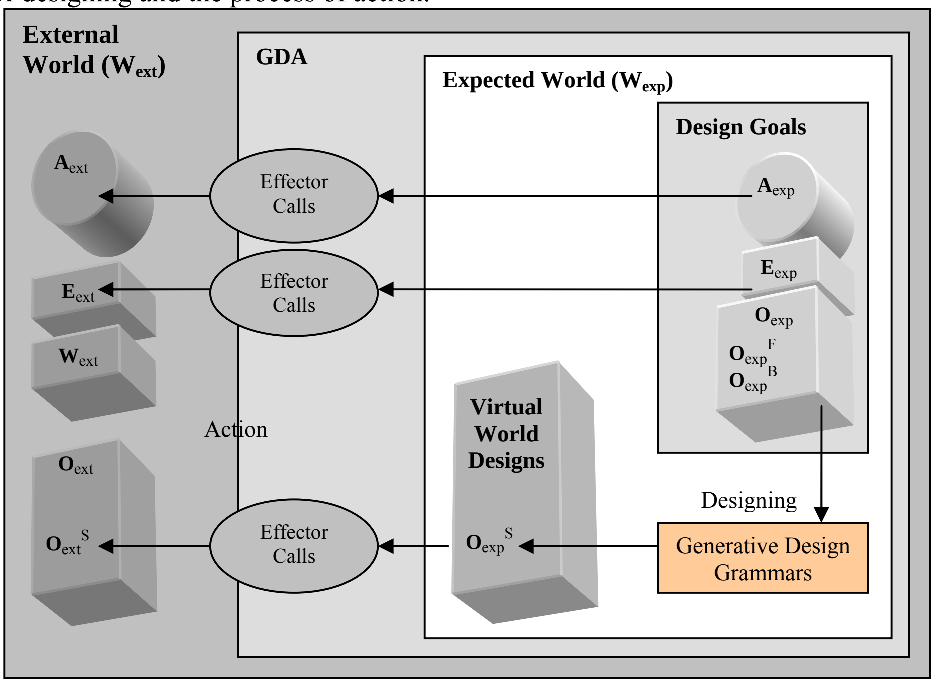


Figure 3.7. The process of designing and the process of action.

The basic components of a generative design grammar are design rules. Each design rule can be expressed in the following form:

$$LHO + sL \rightarrow RHO$$

where LHO refers to left-hand-side object, and RHS refers to right-hand-side object. The term "object" used here can mean a virtual world object, a set of virtual world objects or virtual world object properties. Each design rule is associated with certain state labels sL, which represent specific design contexts that are related to the GDA's design goals. In order for a design rule to be fired the following conditions need to be met:

- The LHO of the design rule is recognised by the GDA in the virtual world, and
- The design contexts represented by the state labels sL of the design rule are related to the GDA's current design goals.

For example, a design rule for generating layouts of a virtual gallery can be illustrated as shown in Figure 3.8.

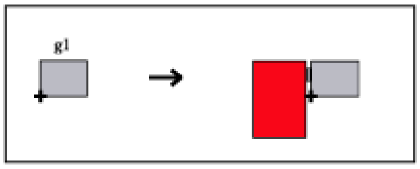
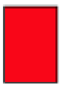
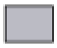
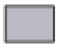


Figure 3.8. An example design rule for generating layouts of a virtual gallery.

In Figure 3.8, the LHO of the design rule is a reception area, and in the RHO, a virtual gallery area is placed spatially adjacent to the reception area.

Symbol  represents a gallery area in the virtual gallery for displaying exhibitions.
Symbol  represents the reception area of the virtual gallery.

The meaning of state label sL=g1 is to generate a certain gallery area in the virtual world. In order for this design rule to be fired, the following two conditions need to be met:

- A reception area  is recognised in the virtual world by the GDA.
- The design context represented by sL=g1 (to generate a certain gallery area in the virtual world) is related to the current design goals of the GDA, represented as O_{exp}^{F} and O_{exp}^{B}.

The application of each design rule replaces the LHO with the RHO, which forms the O_{exp}^{S} or parts of the O_{exp}^{S}. The concept and development of generative design grammars for designing virtual worlds are further explored in Chapter 4. An example grammar for dynamic design of a virtual gallery is presented in Chapter 5, with its application demonstrated in Chapter 6 using a design scenario.

3.4 THE GENERATIVE DESIGN AGENT MODEL AS A DESIGN MODEL

The GDA model is a design agent model. Each GDA is capable of reasoning, designing and manipulating the virtual world as needed. Gero's Function-Behaviour-Structure (F-B-S) framework (1990) uses F, B and S as variables to describe designing in general. Eight processes are depicted from the framework. They are marked as 1 to 8 in Figure 3.9. Gero calls them formulation (1), synthesis (2), analysis (3), evaluation (4), documentation (5) and three different kinds of reformulation (6, 7 and 8).

In Figure 3.9, symbol F represents functions, B_e represents expected behaviours, S represents structures, B_s represents actual behaviours that derive from the structures, and D represents design descriptions. The eight processes proceed in the following order:

- Designing starts with formulation, where the design requirements (understood in terms of functions) are transformed into the expected behaviours.
- In synthesis, the design solution is provided in the form of structures, which intend to support the expected behaviours.
- In analysis, the actual behaviours are derived from the structures.
- In evaluation, the actual behaviours are compared with the expected behaviours.
- If the actual behaviours are evaluated to be satisfactory, documentation will proceed to produce design descriptions.
- If the actual behaviours are evaluated to be unsatisfactory, appropriate reformulation will

proceed to adjust relevant elements and restart the process.

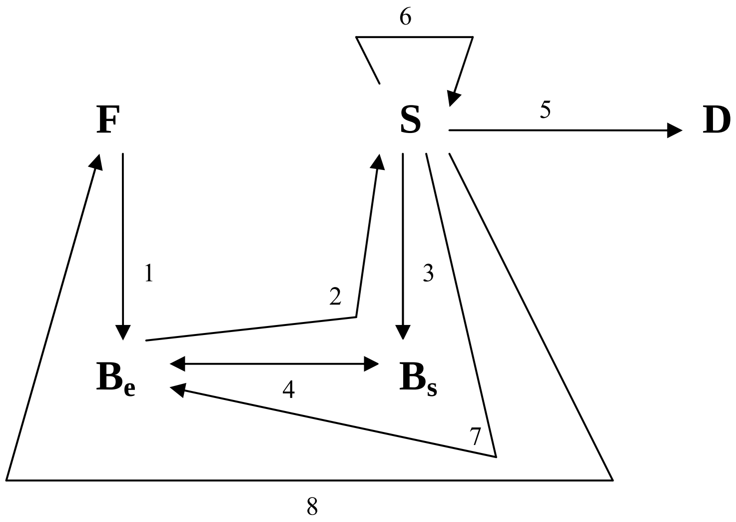


Figure 3.9. The F-B-S framework for describing designing (after Gero, 1990).

The GDA model as a design model is developed based on the above understandings, but with adaptation for designing virtual worlds. As discussed earlier in section 3.2, at any moment a GDA views a virtual world W as the union of the external world W_{ext}, the interpreted world W_{int}, and the expected world W_{exp}:

$$W = W_{ext} \cup W_{int} \cup W_{exp} \quad (3.1)$$

Designing virtual worlds can be represented as interactions among W_{ext}, W_{int} and W_{exp}. There are four processes depicted from the framework of designing virtual worlds. They are marked as 1 to 4 in Figure 3.10: hypothesising (1), designing (2), action (3), and (re)-interpretation (4).

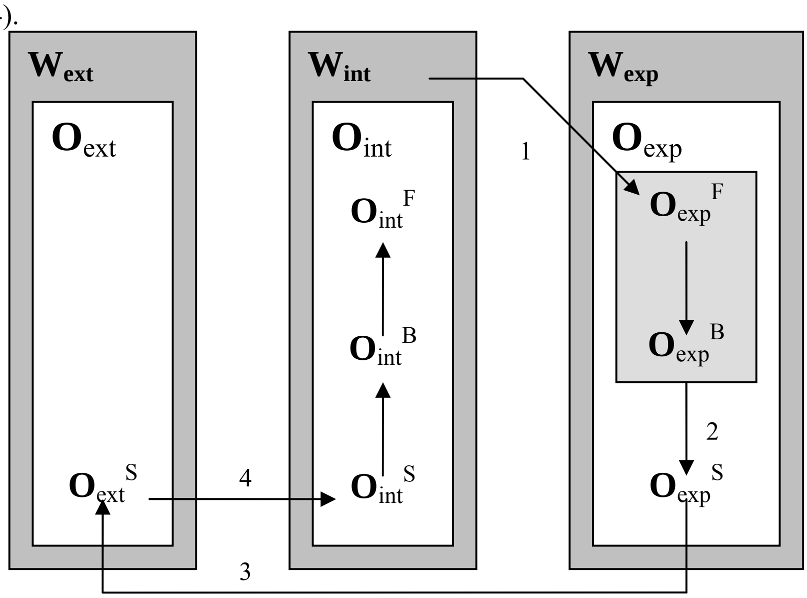


Figure 3.10. The F-B-S framework adapted for representing designing virtual worlds.

Firstly, in hypothesisng, as described earlier in section 3.3.2, the GDA sets up design goals that are related to designing virtual worlds in terms of the expected functions O_{exp}^{F} and the expected behaviours O_{exp}^{B}, in order to eliminate or reduce the mismatches between the current needs of the virtual world occupants N, and the current state of the virtual world sT, interpreted by the GDA.

$$O_{exp}^{F} = \{O_{exp\_1}^{F}, O_{exp\_2}^{F}, \dots , O_{exp\_n}^{F}\} \quad (3.9)$$

$$O_{exp}^{B} = \{O_{exp\_1}^{B}, O_{exp\_2}^{B}, \dots , O_{exp\_n}^{B}\} \quad (3.10)$$

for any expected function $O_{exp\_i}^{F}$ and expected behaviour $O_{exp\_i}^{B}$:

$$O_{exp\_i}^{F} \in \tau(N, sT)$$

$$O_{exp\_i}^{B} = \tau(O_{exp\_i}^{F})$$

Secondly, in designing, as described earlier in section 3.3.3, the GDA applies its generative design grammar to provide a virtual world design for the moment to satisfy its current design goals or parts of the goals.

$$O_{exp}^{S} = \tau(O_{exp}^{F}, O_{exp}^{B})$$

Thirdly, in action, the actions for implementing the generated virtual world design are planned, and the planned actions are activated in the virtual world via the GDA's effectors.

$$O_{exp}^{S} \rightarrow O_{ext}^{S} \quad (3.12)$$

The implementation of the generated virtual world design causes changes to the virtual world, which triggers (re-)interpretation.

$$O_{int} = \tau(O_{ext})$$

for any interpreted virtual world object O_{int_i}:

$$O_{int\_i}^{S} = \tau(O_{ext\_i}^{S})$$

$$O_{int\_i}^{B} = \tau(O_{int\_i}^{S})$$

$$O_{int\_i}^{F} = \tau(O_{int\_i}^{B})$$

The GDA interprets the new sense data from the virtual world. If the newly interpreted N and sT has no mismatch, designing virtual world will terminate for the moment. Otherwise, a new cycle of hypothesising, designing and action will start.

Comparing Figure 3.10 with Figure 3.9, in designing virtual worlds, by applying the GDA model, the design life-cycle is shortened. This highlights the characteristics of such a kind of virtual world as a different kind of architecture that exists for the moment. They are sensitive to changes in the worlds and respond to changes in a very fast pace.

- Using the GDA model, designing virtual worlds becomes inseparable from design implementations. Design descriptions generated by the grammar application are only stored temporarily in the GDA's expected world before being implemented.
- Compared to designing in general, designing virtual worlds using the GDA model does not explicitly specify design evaluation and reformulation. The original processes of evaluation and reformulation are integrated into (re)-interpretation. After a virtual world design is implemented, the GDA interprets the actual implemented design, and starts a new cycle of hypothesising, designing and action to make adjustments, if necessary.

3.5 DISCUSSION

A GDA is a rational design agent, which has a reasoning mechanism that is specifically developed for reasoning and designing in virtual worlds. The design component of a GDA is supported by the application of a generative design grammar. Applying the GDA model, virtual worlds are distinguished from the physical world and other static virtual worlds that are pre-defined prior to their uses, and become dynamic as the GDA model enables virtual worlds to be designed, implemented and manipulated as needed.

3.5.1 The GDA Approach to Designing Virtual Worlds

The characteristics that make the GDA approach to designing virtual worlds distinctive are summarised below.

In terms of representation:

- The GDA model is especially suitable for reasoning about and designing dynamic, non-static virtual worlds. For each GDA, the representation of a virtual world is constructed in terms of three different views: $W = W_{ext} \cup W_{int} \cup W_{exp}$.

In terms of designing:

- Differently from the conventional approach to designing virtual worlds, and using the GDA model, firstly the design and implementation processes of virtual worlds are automated. Secondly, designing virtual worlds becomes an internal process that occurs inside the worlds and is influenced by the worlds. Previously, these processes were mainly controlled by designers outside the worlds.
- In contrast to other agent-based approaches where agencies are provided to existing virtual world components like walls, doors, rooms, buildings and so on, the GDA approach provides agencies to the virtual world occupants. Shifting the agencies from existing virtual world components to virtual world occupants frees virtual worlds from being pre-defined. In the GDA approach, rational design agents are applied to dynamically design virtual worlds for different purposes during the use of the worlds, rather than to reason about and modify existing designs of the virtual worlds.

In terms of the roles of human designers:

- In most virtual worlds that currently exist, the design tasks rely heavily on human designers. In general, the designers produce virtual world designs and implement them to support different activities online. In later stages, the implemented designs may be reused, modified or demolished by the designers for other purposes. However, in these virtual worlds the general occupants, who inhabit the environments can rarely influence the design process and make changes to the worlds during their uses.
- Using the GDA model, human designers define generative design grammars that produce different design languages for the virtual worlds, rather than pre-define every detail of all possible virtual world designs. The actual design tasks are carried out by the GDAs during real-time interactions in the worlds. GDAs can apply different generative design grammars to generate virtual world designs for different purposes and with different stylistic characterisations.

3.5.2 Designing Virtual Worlds as Individual and Collaborative Acts

The GDA model developed in this study focuses on its support for dynamic designs of virtual worlds. This chapter hence focused on detailing the five computational processes of the model, which are specifically developed for a GDA to reason, design and act in the virtual worlds. Designing virtual worlds has so far been explored in terms of individual processes by the GDAs; for example, when a design problem arises in a multi-GDA virtual world it is assumed that a dominant GDA will reason, design and act on behalf of the occupants.

However, the reasoning mechanism of the GDA model enables each GDA to reason about the virtual world as well as other GDAs in the world. The GDA model is applicable to collaborative designs of virtual worlds if agent communication is established. Although agent communication is beyond the scope of this study, it is one of the major extensions of the study. This is discussed in Chapter 7 section 7.4.