A systems-level understanding of adversarial behaviour

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Abstract: Modelling behaviour related to the perpetration of improvised explosive devices is extremely complex. Behavioural aspects range from those who create a plan to those who gather supplies for developing the devices to those who passively look the other way. Developing computational approaches to understanding such behaviour necessitates either a decomposition of behavioural activity into smaller, manageable behaviours or generalising larger, group behaviour where gross trends are observed. This may suffice for particular applications; however, additional consideration can be given to developing more comprehensive approaches. Specifically, for those seeking to understand terrorism, a number of social, cultural and behavioural perspectives are being developed by experts worldwide. These perspectives may complement each other or they may be in conflict, but they equally contribute to a broader understanding. Our research is developing computational methods to analyse and experiment with differing views and perspectives of potential influences on adversarial behaviour at this system-level.

Keywords: recruitment; adversarial behaviour; violent extremists; multi-scale modelling; multiple perspectives; improvised explosive devices.

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1 Introduction

In a 2008 presentation to the New York Police Department, Dr. John Horgan noted that in trying to understand violent extremists and in developing approaches to disengaging individuals from terrorisms, answers cannot lie in any single theory (Horgan, 2008). Instead, knowledge from multiple disciplines is needed and must be aggregated within more conceptual frameworks. Furthermore, many approaches from psychology and criminology are still underdeveloped and could benefit from alternatives to traditional theoretical approaches in evaluating their effectiveness. Computational models offer an approach to support development of these theories by expanding the ability to explore aspects of socio-cultural influences and to identify potential indicators that increase a person's propensity to being radicalised, recruited, disengaged, or even de-radicalised from adversarial behaviour.

Behavioural and cultural models are useful in assisting analysts and decision-makers in understanding activities and behaviour of violent extremists. Models are also useful for analysis and experimentation on the impact of potential influences on population behaviour. The multiple modelling paradigms that have emerged represent different aspects of this space, where subject matter experts are often used to help couple social behaviour and theoretical aspects with quantitative modelling approaches. By integrating behavioural aspects of adversarial activities with computational methods, wholly new approaches can be developed to support what-if experiments related to understanding these activities and to ascertain potentially effective intervention points to disrupt the process of individuals engaging in adversarial behaviour (Briscoe et al., 2010a, 2010b, 2011; Weiss et al., 2010, 2011).

Many existing models that attempt to conceptualise these dynamics typically offer a fixed perspective rather than integrating multiple perspectives across multiple scales, even within a single discipline (Zacharias et al., 2008). There has also been limited success in integrating qualitative, process-based perspectives into computational models. The research presented here seeks to capture multiple perspectives of behaviour in a systems approach to support computational assessments of differing perspectives and to support an analytic understanding of influences on adversarial behaviour. In addition, the conventional approach to federated models involves specific submodels which are typically designed to be part of a larger, federated system (Benjamin et al., 2007). Our research, on the other hand, explores techniques to identify multi-scale phenomena (macro, meso, and micro-scale) and to capture them through connecting concepts within a modelling construct. Specifically, these models can begin to capture the process by which individuals become radicalised as a function of multiple-scale events such as personal experience (alienation), recruitment into radicalised groups, and societal policies. This approach then enables communication among models that were developed by a variety of parties by federating them via model-docking methods that define points of interaction and transformations for data exchange. In particular, this permits individual models to maintain their intended composition while allowing other models to act as providers of relevant, external information.

2 Representations of human behaviour

Theorists often refer to behaviour as represented in micro-meso-macro scales (individual, group, organisation, community, institution, society, and global order being the most commonly used scales in sociology). This division is often attributable to two causes. The first is that there may actually be some natural levels of differentiation on which researchers identify and develop focused theories. The other is that humans tend to decompose subjects to understand them from our own level of perception (Goguen and Varela, 1979). This approach identifies system boundaries according to the constraints imposed by human limitations in comprehending more than one scale at once. Studies on the importance of these divisions have a long history in many areas of science and philosophy, though the concentration on lower scales (sometimes referred to as reductionism) is most present in contemporary science (Goguen and Varela, 1979). Some disciplines concentrate primarily on large-scale (macro) theories of behaviour (e.g., political science). Cognitive psychology, on the other hand, focuses primarily on the individual (micro) level of behaviour. Economics, in particular, has clearly delineated this difference in its two primary concentrations, macro- and micro-economics (Dopfer et al., 2004). Despite this separation, many issues related to human behaviour involve influences that exist across a range of scales, from the individual level to that of whole societies or cultures.

When modelling individuals as part of a group or society, a single modelling paradigm may be inadequate to capture the nuances and interactions within the domain. Individual and group-level behaviours are often modelled using agent-based models to represent causal relationships among individuals (Bonabeau, 2002). This allows the internal attributes of an individual to be incorporated within the model. Societal behaviours, on the other hand, are often modelled using paradigms that focus on trends among large numbers of people and can be incorporated using methods such as system dynamics modelling (Sterman, 2002). This allows the representation of high-level behaviours that are not apparent among individuals or even groups of individuals. Other models may encompass system behaviours in completely different ways. Each modelling paradigm is often suited for a particular type of representation, so there is value in maintaining the information content of existing models while allowing them to interact to represent the behaviour of broader systems.

Having models that share knowledge (as opposed to raw data) provides numerous benefits. Most obvious is the ability to represent critical aspects of behaviour within a flexible framework that accurately and efficiently captures the most important features. There is also great value in the ability to understand and experiment with conditions and inputs of different models across scales. A much greater level of transparency is provided by modelling a complex topic, such as human behaviour, with a multi-scale approach. As such, combining information across multiple scales may reveal new insights into the topic at hand. This paper builds on existing social theory and presents an approach to identifying the types of interactions that exist between multiple scales of human behaviour representations and how those interactions may be realised by linking independent multi-scale models.

3 Interactions across scales

A loosely structured classification of the types of information most commonly communicated across scales could facilitate an analytical approach to sharing information among models that represent different behavioural aspects and scales of the same general problem. Past classifications stem from sociological research on *mechanisms*, which are social processes with designated consequences for specific parts of the social structure (Merton, 1967). One classification by McAdam et al. (2001) distinguishes among environmental, cognitive, and relational types. Environmental mechanisms produce changes in 'the conditions affecting life'. Cognitive mechanisms refer to psychological mechanisms driving specific kinds of behaviour; and relational mechanisms alter the connections among people, groups, and interpersonal networks. These mechanisms primarily exist on two scales of analysis, micro and macro; however, more relevant to using multi-scale models to understand a particular aspect of behaviour would be to more finely classify the types of interactions that occur across micro, meso, and macro-scale analyses.

Multi-scale interactions have been traditionally perceived as more often flowing upward, from micro to macro, where the macro-scale effects are directly created from individual actions (Mayntz, 2003). Hedström and Swedberg (1966) referred to this interaction as *transformational*, where individuals' interactions are transformed into a collective outcome. This interaction is readily identified when macro-scale phenomena appear as emergent effects of interdependent agents; however, individual actions implicitly eliminate structural features from the relationship directly responsible for a macro-scale phenomenon. For example, in the adoption of new technology (Briscoe et al., 2010a) the belief structure of each individual determines whether one will adopt a new behaviour, but the shape of the whole process, how quickly it spreads, or whether it diminishes early is entirely dependent upon the social structure in the population and the profile of receptiveness over all individuals. A similar case can be made for adversarial behaviour, as in the radicalisation of individuals toward terrorism. For example, alienation experienced by an individual may result in one joining a terrorist group with other individuals who experience similar alienation or social problems.

This importance of structure supports the need for formal inclusion of an intermediate scale between the micro and macro scale representations. For example, individuals may act together to form groups (such as violent extremist organisations) that are too small to be modelled at the societal level and are thus best represented as an intermediate, meso-scale entity. These groups (which could be modelled as collective agents) possess qualities derived from the sum of the individuals as well as qualities unique to the group itself. This group-identity provides social structure coherence and cognitive capacities (Goguen and Varela, 1979). We identify this as a *formational interaction*, which represents the relevant individual qualities used to create the group identity. The specific qualities depend on the domain of interest; however, it is likely that they will relate to those factors identified in the psychological literature on group behaviour, such as overlap in belief structure (Hastie and Kameda, 2005).

In the opposite direction, meso-scale qualities that are relevant to individual behaviour are equally important. Individual-level models of behaviour often use social network information to represent the availability of information and influence. For example, to understand an individual's attitude toward a particular idea, it may be necessary to know who is closest to him (in terms of social connections) to determine the influence. We term this interaction *structural* since the structural properties of an individual's social (or political, religious, etc.) group are relevant at the micro-scale level. These interactions may also include information about the group's identity since it exists separately from the individual. For example, if a highly susceptible, but non-radical individual becomes a member of a radical group, the influence of that group's beliefs is highly relevant to the individual's behaviour, where one might expect polarisation to occur (Zacharias et al., 2008).

Hedström and Swedberg (1966) used the term *situational* to describe mechanisms that link macro-sociological states to the beliefs and opportunities of individual actors (macro-micro interactions). This type of interaction is critical to capturing society-wide influences. For example, economic and military policies of a government or environmental conditions and events are the 'backdrop' to individual behaviour. Likewise, we suggest an additional term, *contextual*, for those macro-scale societal influences that affect meso-scale behaviour, in that meso-scale behaviour is also constrained by the context in which it occurs. In turn, high level events, represented at the macro-scale, are directly influenced by meso-scale behaviour. We term this interaction as *conversional*, where the beliefs of groups are likely to convert to larger-scale changes. For example, if violent extremist group declares the US an enemy, US policy is likely to change toward that group and those affiliated with it.

These terms and classifications are summarised in Table 1.

Table 1 Classification of multi-scale interactions

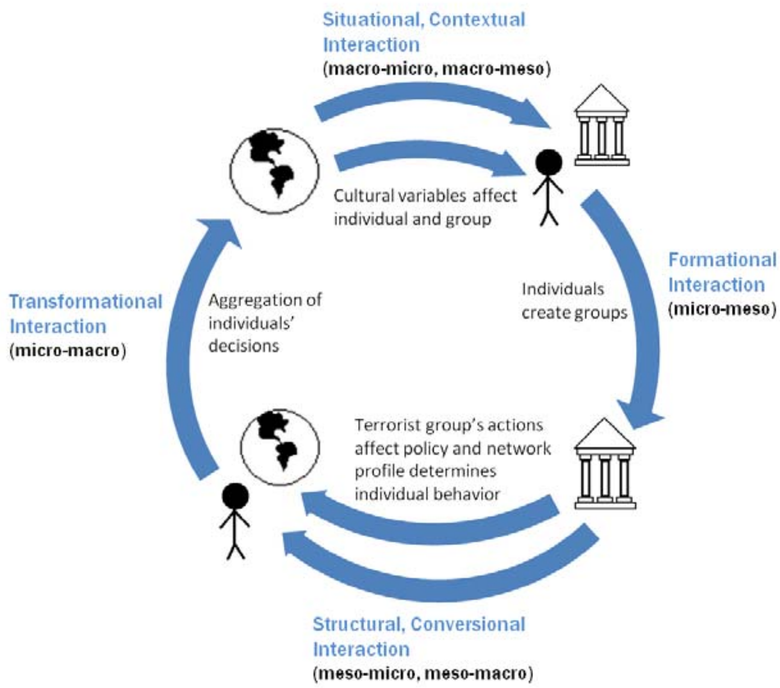
Term	*Description*
Situational*	Macro-micro interactions
Transformational*	Micro-macro interactions
Individual action*	Micro-micro interactions
Conversional**	Meso-macro interactions
Contextual**	Macro-meso interactions
Structural**	Meso-micro interactions
Formational**	Micro-meso interactions

Notes: *From Hedstom and Swedberg (1996)
**defined in this paper.

Figure 1 depicts how these interactions arise in modelling a specific scenario of the recruitment of an individual into a violent extremist group (see Briscoe et al., 2010a, 2010b; for details on macro-level modelling of this scenario). At the first step, there is the cultural isolation that, for example, a Somali-American Muslim youth may feel growing up in the USA, which may result from macro-scale cultural factors (e.g., Hofstede's *Individualism*). These macro-scale factors may provide the conditions in which the micro-scale representation results in the individual's decision to seek out an online extremist group that he or she feels offers a source of social capital. These factors may also influence the recruitment efforts of the extremist group. The extremist group is best represented at the meso-scale, since many extremist groups recruit as an organisation.

The group's recruitment ability, or reach, may be represented through a connectivity profile at the meso-scale, which may indicate the likelihood that an individual would be able to make contact with a recruiter. This meso-scale quality associated with the recruitment effort on behalf of the group may also be a causal factor in the government (at the macro-scale) affecting policy change. Once contact is made with the individual by the extremist group and recruitment is possible, the cognitive factors that affect an individual's decision to join and participate with the group are best represented at the micro-scale. These micro-scale decisions may then be aggregated into macro-scale variables, for example, to represent an increase in the number of radical Islamists in the US, which may in turn, affect the same cultural variables with which the example began.

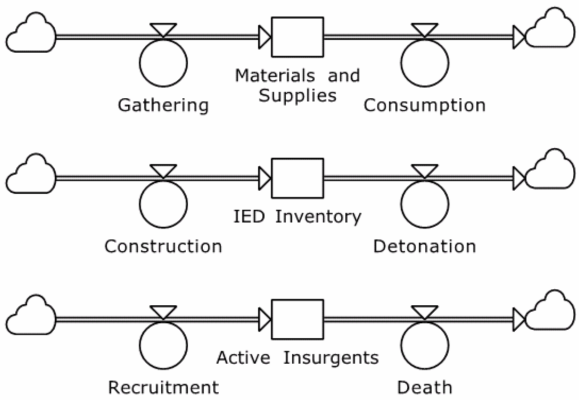
Figure 1 An example of information flowing across multiple scales of representation of the recruitment of an American youth into a violent extremist group (see online version for colours)



4 System dynamics model for macro-scale IED activities

Our previous work in understanding adversarial behaviour associated with the creation and placement of IEDs resulted in a computational model of macro-scale behaviour using a system dynamics approach. This type of model is used to represent the dynamic behaviour of a complex system over time (Sterman, 2002). System dynamics is a modelling approach that uses *stocks* and *flows* to represent system elements and their relative influences on each other. Figure 2 presents an extremely simplified schematic of IED perpetration using stocks and flows. Stocks represent an inventory of an accumulated entity (e.g., materials and supplies, IEDs, people) and are indicated in the model using rectangular boxes. Flows, indicated by a double-lined arrow, show how entities move between stocks or between a stock and a cloud. Clouds, which may take the place of a stock, indicate the world outside the scope of the model and act as either sources or sinks. Thus, for example, materials and supplies and obtained by gathering, and these materials and supplies are then transferred to the world outside via consumption.

Figure 2 Extremely simplified macro-scale IED model



We acknowledge that the development and deployment of IEDs, as reflected in Figure 2, represents only one of many complex roles and functions to be performed by members of violent extremist groups, but it serves as a useful illustration of our framework. Flows represent the transfer of entities in the system through a valve that specifies the movement between stocks. The naming convention for each valve uses a noun that represents the transition action of elements between two stocks. In the model, these valves indicate potential cut-off points within the IED process. Each flow has a customised expression that determines its value at a given time, based on any related variables that influence its value. Stocks generally have a fixed expression based on any flow (or *rate*) into or out of each stock, in which each stock's value is the integral of all in-flows minus all out-flows. Thus, each flow is proportional to the derivative of the stocks it affects, which means that it represents the rate of change of those stocks. For example, changes in amount of gathering changes the amount of supplies and materials present, which then affects the level of consumption of those materials. During model execution, the model calculates the value of each stock, flow, and any auxiliary variables based on the related variables and the expressions that govern each element. Simulation occurs over a span of time, once per time-step. The time-step and maximum time duration is adjusted to alter the resolution and duration of the model execution.

Figure 3 More detailed IED perpetration model (see online version for colours)

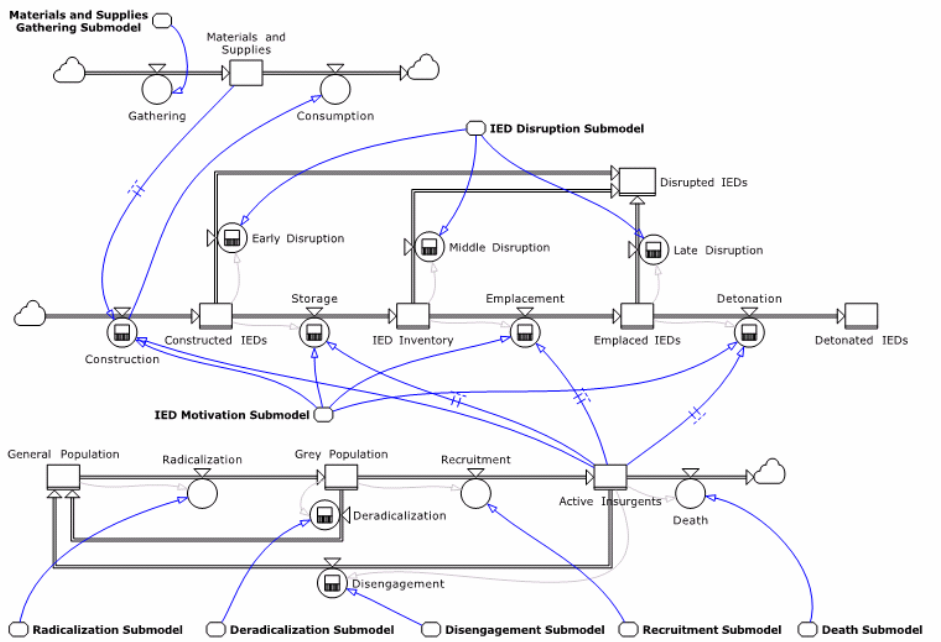
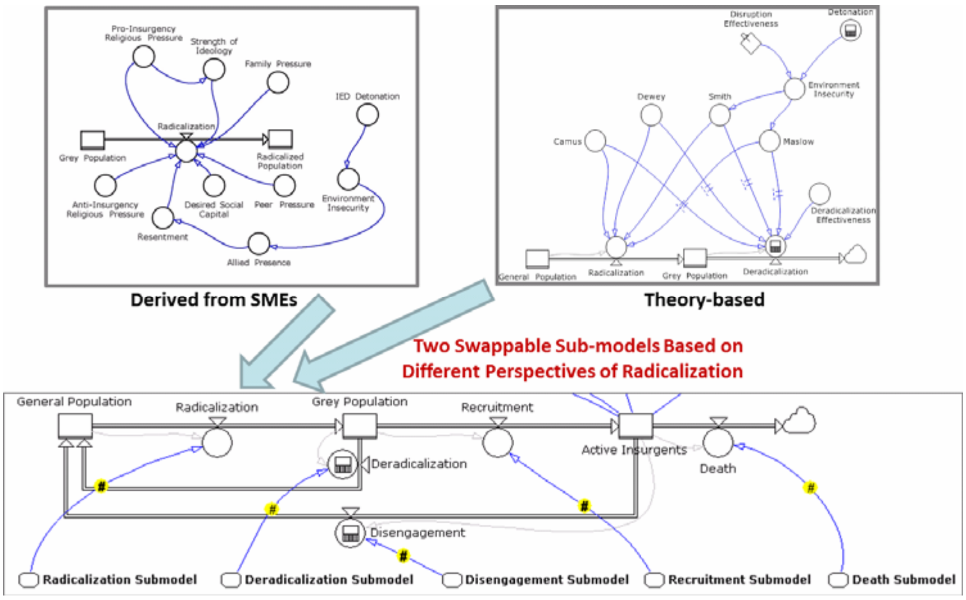


Figure 3 represents an expansion of our IED perpetration model, where content details are based on literature and inputs from subject matter experts to allow for the representation of multiple scales of behaviour. Here, the model captures behaviours and influences at the macro-scale, while submodels are incorporated to reflect meso- and micro-scale behaviours. For example, gathering materials and supplies represents a micro-scale of the IED process. Thus, construction of the IED on a micro scale feeds into activation and/or disruption of the IED with more people involved in the process. All of these sub-models then feed into the macro model that describes the entire process of constructing, emplacing, and detonating IEDs. Meanwhile, at the bottom of the figure are models that pertain to radicalisation of a person or group of persons. The radicalisation and recruitment submodels are micro and meso-level models, depending on if the focus is an individual being recruited (micro-scale) or groups of radicalised individuals forming and recruiting individuals (meso-scale). All of these submodels support an overall model of radicalisation which may occur at the macro-scale. An attractive feature of this compilation of models is that, as information is gained, it can be incorporated into the modelling paradigm and expanded either by upgrading the submodels or by docking external models. For example, the submodel of disengagement may provide new information regarding how a community attempts to de-radicalise members of the community, thus reducing terrorism. The discussions below describe the types of information and approach that can be integrated and used within these models for analysis by enabling interchangeable submodels for multi-scale analysis.

5 Modelling multiple perspectives at multiple scales

The previously described model of IED-related activities emphasised the complexity of the issue and is representative of the fact that addressing the threat of terrorism has led to multiple, diverse opinions and theories as to its causes, indicators, and influencers. This diversity arises not only from differences in opinions and exposures, but also from the originating disciplines and backgrounds of the analysts. Whereas our previously described models captured multiple scales of behaviour in a single construct, we now describe a framework in which agnostic, independent models that reflect different perspectives of adversarial behaviour may be combined (or docked) to provide an analyst with increased computational flexibility. Within our prototype framework, we capture micro and meso-scale perspectives using agent-based models that communicate with representative models of radicalisation within a macro-scale system dynamics framework. This approach allows different models at different scales to interoperate with and be swapped out for other models of the same phenomena developed by other parties, without the requirement of a system design that incorporates the specific models from the start. Having a suite of swappable models allows for evaluation and assessment of different views, so that a model based on a particular set of assumptions about culture or behaviours can be replaced by a different model. This is schematically captured in Figure 4. Namely, models of radicalisation based on different theories or opinions can be merged with the overall model to understand how the effects of radicalisation manifest at a macro-level scale.

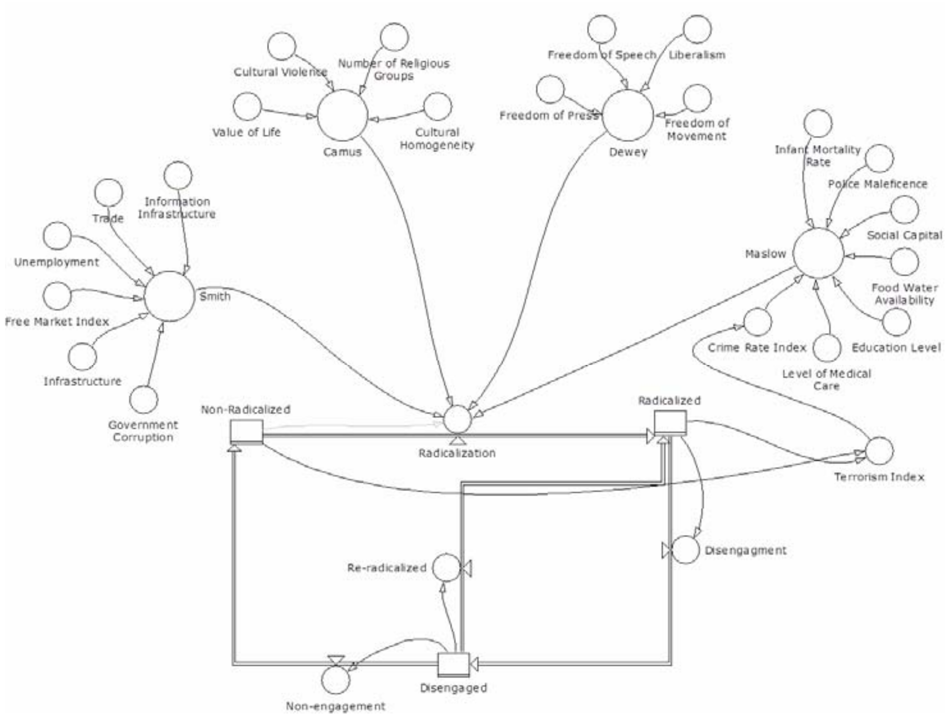
Figure 4 Two sub-models of radicalisation based on different perspectives that can be inserted into or docked with the larger-scale system dynamics model of behaviour (see online version for colours)



For illustration, the remainder of this paper presents a macro-scale system dynamics model and two meso/micro-scale agent-based models that were created to represent aspects of the process of a person becoming involved in adversarial behaviour. These models describe facets of micro-scale behaviour associated with individuals, as well as meso-scale behaviour arising from groups of people. Micro and meso-scale factors interface with a macro-scale system dynamics model to provide a comprehensive picture of adversarial behaviour that may be compared to one incorporating other micro-scale theories of radicalisation.

The macro-scale model is a perspective of the radicalisation process (illustrated in Figure 5) derived from that described by Bartolomei et al. (2004). Here, various factors that contribute to a person becoming radicalised are categorised into four groups that encompass critical influential variables, namely, Smith (economic), Camus (cultural), Dewey (freedom), and Maslow (quality of life). While this model is a fully independent functioning model, it serves as an example of a comprehensive macro-scale model that represents high-level variables relevant to the radicalisation process, without representing any specific individual behaviour.

Figure 5 Macro-scale model of the radicalisation process based on Bartolomei et al. (2004)



The two agent-based models used represent micro-scale behaviour and embody alternate ‘pathways’ to ‘homegrown’ terrorism as described by Gartenstein-Ross and Grossman (2009). These models are agnostic in that they have not been specifically developed to interoperate with each other or with any system dynamics model of radicalisation. Instead, they are self-contained reflecting attributes and thematic focuses specific to the perspectives being modelled. A summary of each model is provided to glean an appreciation of the level of multi-scale interactions involved.

The first agent-based model depicts radicalisation as caused by religious ideology. Though certainly not the only contributing factor and often a contentious topic, religious ideology may play an important role in the radicalisation of individuals. To represent the situations in which ideology is a primary instigating factor to adopt radical beliefs (leading to violent extremist acts), the agent-based model simulates radicalisation as resulting from relationships with religious leaders who encourage radical ideas. Within this model, the actions of the population are captured by the formation and dissolution of friendships between individuals and the resulting changes in those individuals in terms of their (simplified) beliefs related to radicalised behaviour, such as personal attraction, persuasiveness, or charm of others(represented via other agent models). At the micro level, a person's 'fervour' represents his or her religious status in terms of his or her desire to convert others, or his or her motivation to try to change the world based on his or her own religious beliefs. Each person is associated with a neighbourhood, religion, and specific church, each of which is used to characterise the likelihood of various members of the population becoming friends during a particular time step within the model. In this model, a spiritual mentor is defined by a particularly high personal relationship combined with a high fervour. At the meso level, friendships are randomly formed between members of the population at rates based on their neighbourhoods, religions, and churches, and have strengths associated with them to capture the different levels of friendship between people, ranging from casual to intimate. Spiritual mentor-mentee relationships may also be formed, where for each encounter, the mentee becomes more radicalised. A mentee whose fervour reaches a certain height is then considered a radical. Thus, micro and meso models are connected.

The second agent-based model was developed to capture factors that contribute to the adoption of terrorism resulting from clique formation (meso-scale) and the feeling of isolation (micro-scale). The primary concept of radicalisation in this model is based on the formation of small social groups or cliques. Once the clique is formed, the group can radicalise in a manner which none of the individuals would have demonstrated separately. This model focuses on the formation of the cliques that enable this form of radicalisation rather than on the radicalisation process thereafter. The formation of the cliques is modelled primarily as dependent on a single variable, the feeling of isolation. The cliques are formed via the assembly of people with similar backgrounds (religion and home country) who have similar experiences in their current country. The 'isolation' of a person represents his or her alienation from society and thus is at a micro-level scale. This feeling is increased by interactions with members of the majority who have nothing in common with that individual or by interactions with minority members who are experiencing the same isolation. For most of the population, these feelings are offset by the presence of diverse friends and family who provide adequate emotional support and context to their interactions with the majority. All of the minority population is assigned a family that can include extended relatives, in-laws, and very close friends who have been close since childhood. These ties are considered closer than the average friendship. At each time step, friendships are randomly formed between members of the population based on their personal backgrounds, and friendships are also randomly dissolved since few people who meet during random encounters rarely become close friends (meso-scale). Once a clique link is established, it puts a strain on the other relationships existing with those two people. Their intimates and acquaintances are effectively forced to choose to join the clique or cease having a relationship, as time passes. This represents the clique's reduced tolerance for other perspectives, whether they pertain to society, religion, politics, or something else. Thus, micro-scale factors such as isolation feed into meso-scale factors such as clique formation and tolerance, which can then have impact on micro-scale factors – namely, strengthening the radicalisation of individuals. In this model, no distinction is made between the types of cliques formed, nor how those cliques may choose to handle their isolation from society. Since the actual rate at which people become radicalised is quite low, some of the agents' rules and probabilities can be adjusted so that the process of radicalisation can be visualised in a relatively small number of time steps.

6 Model interoperability

The agent-models just described, like most, are often built upon different theoretical foundations. While any two models may represent similar aspects of a culture, they may use different terminology, time scales, syntax, or grammar. A common vocabulary for models of the same system enables easy substitution of models, but such a shared vocabulary does not exist among models developed by different parties. Experimentation among different models with disparate vocabularies is enabled by providing a transformation to convert concepts between models.

Tolk and Muguira (2003) provide *Levels of Conceptual Interoperability* to describe the degree with which models are interoperable. They are summarised in Table 2 and begin with level 0 of disconnected models. Our research enables level 3 interoperability by creating a framework of Connecting Concepts to dock multi-scale models, and in particular, to dock agent-based micro and meso-scale models with macro-scale models. The approach uses transformation functions such as aggregation or distribution of data between pairs of models, and supplies the semantic relationships for level 3 interoperability. The current research still requires manual connections, but it provides a library of functions to be reused and modified to enable the connections to reflect the expert view of how variables transform when they move from one model to another. As the research progresses, a more computational implementation of these relationships will be developed to move toward higher levels of interoperability without manual connections.

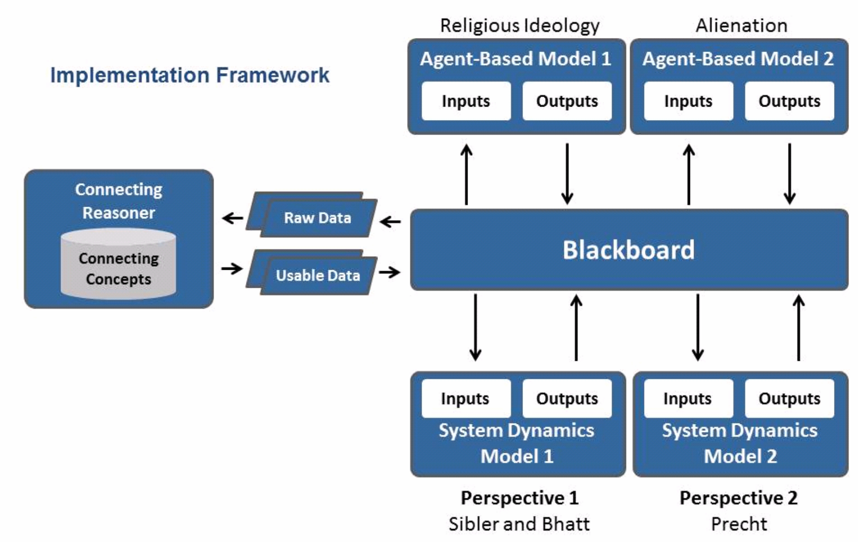
Table 2 Tolk and Maguira's (2003) levels of conceptual interoperability

Level	*Description*
Level 0	No connection
Level 1	Physical connectivity allowing messages to be exchanged
Level 2	Syntactic level (protocols and formats)
Level 3	Semantic level (meaning of data is defined by common reference models)
Level 4	Pragmatic/dynamical level (information and its use and applicability)
Level 5	Conceptual level (common view of the world: knowledge and relationships among concepts)

6.1 Blackboard implementation

The implementation of model interoperability is via a blackboard system (Engelmore and Morgan, 1988), where a 'blackboard' stores partial model data, e.g., information that the models have generated, which may be of use to other models. In this way, the blackboard supports asynchronous, opportunistic modelling by a group of submodels that collaborate indirectly. The asynchronicity enables models to take information when they need it based on their individual timescales and supports model docking, as depicted in Figure 6. This allows the previously described agent-based and system dynamics models to exchange information even though they do not necessarily execute simultaneously. Each model contributes any potentially useful information (in a format convenient to the contributing model) without necessarily modifying the structure or content of that information for use by other models. This encourages each model to contribute as much information as possible, but may require the receiving models to interpret or restructure incoming data before that data can be used.

Figure 6 Implementation framework for modelling multiple socio-cultural perspectives (see online version for colours)



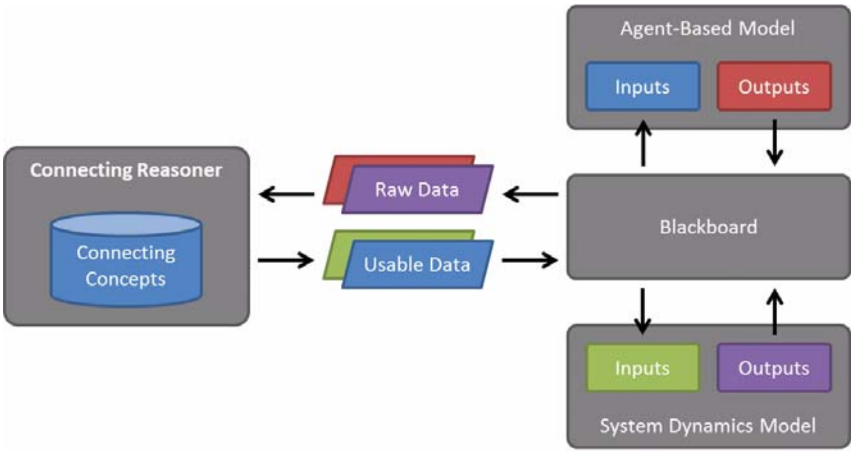
Notes: Not all models execute simultaneously. Rather, combinations are selected to develop an understanding of behaviour exposed from the different combinations of perspectives.

6.2 Connecting concepts

In a blackboard system, any data written by any model is available to all other models within the system. In traditional, federated systems containing models that were developed specifically to interoperate, data written by one model is specified in a way for it to be read specifically by another model as opposed to all other models. Since the interfaces are specific, there is no need to translate data between models. However, when experimenting with multiple models that were not designed to interact, the data written by one model will not necessarily exist in a format usable by another model. This necessitates the use of some means of translating data from one model into the other, which we identify as the *connecting concepts* function.

The connecting concepts define the types of inputs and outputs of models along with transform functions that convert the outputs of various models to inputs of other models. A *Connecting Concepts Reasoner* is used to perform variable transformation during federated model execution. Figure 7 depicts how data flows from the models through the blackboard to the Connecting Concepts Reasoner which then acts as an intermediary that monitors the blackboard for particular types of data, creates a transformed version of that data, and writes the transformed data back to the blackboard.

Figure 7 The connecting concepts reasoner within a blackboard system (see online version for colours)



The simplest transformation is a one-to-one relationship between the input and output data structures from two models, which may involve renaming variables or converting units. Transformations are typically more complex when docking models that operate at different scales. Two such transformations that are used regularly are Distribution and Aggregation. Distribution transformations (Figure 8) support one-to-many relationships, typically based on probability distributions to convert a single output into multiple inputs. Aggregation transformations (Figure 9) support many-to-one relationships, combining many outputs into a single input.

Transformations may also involve conditionals that instruct the receiving model(s) to accept an input only under certain conditions. For example, a distribution function may specify that a subpopulation of models is to receive the output of a higher-level model, as shown in Figure 10. By allowing transformations to be specified via functions, more complex transformations can be attained.

As an example of how transformations support interchanging models, consider the previously described micro-scale models of radicalisation. In the first, identification results from an agent building a close relationship with a mentor; in the second, identification occurs when an agent finds and begins to relate to a violent extremist group. Both conceptualisations require that the agent-based models provide information in terms of an aggregation of those agents who exhibit strong mentor relationships (in the first perspective) or negative relationships with culturally-opposite groups (in the second perspective). By using aggregation, this information can be communicated to the macro-scale model. Similarly, the agent-based models may provide individuals who identify with a particular culture. This information passes through the Connecting Concepts Reasoner, which computes, via an aggregation, the percentage of the population that identifies with each particular culture. This is then used within the macro-scale system dynamics model to represent the degree of isolation. The result is that the construct of model docking with transformations and connecting concepts enables interoperability among independently developed models.

Figure 8 Distribution transformation converting single output to many inputs from a meso-scale model to several micro-scale models (see online version for colours)

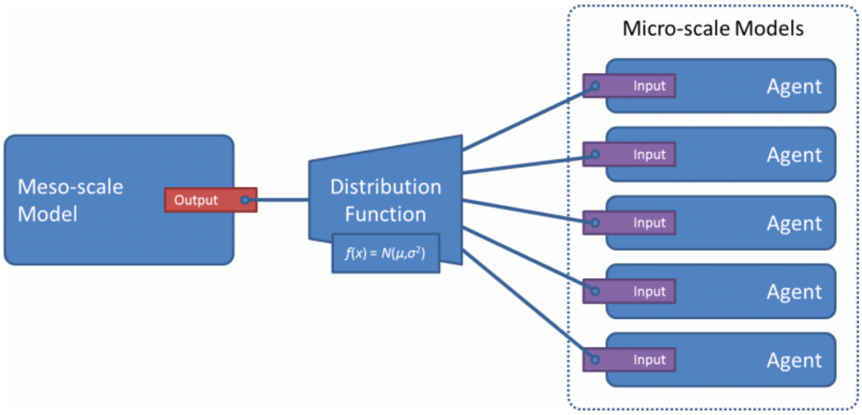


Figure 9 Aggregation transformation converting multiple outputs to a single input from several micro-scale models to a meso-scale model (see online version for colours)

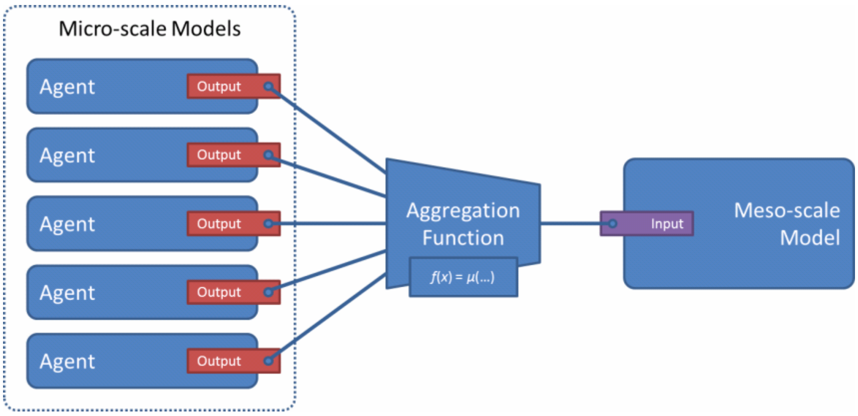
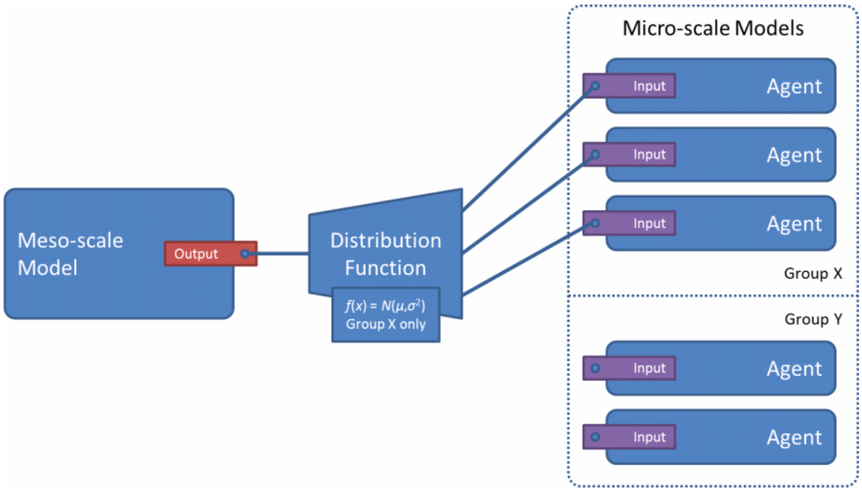


Figure 10 Distribution transformation function selectively applied to a subgroup of models (see online version for colours)



7 Running interoperating models

Figure 11 displays a screenshot of the interface that an analyst would see when using the prototype modelling framework to create transformation between multiple models. The box on the right side of the figure identifies the variables available in two of the models. The centre box then enables a quantitative mapping between the variables of the submodels. Figure 12 depicts the corresponding output from running the two different agent-based models docked with the macro-scale model and demonstrates the ability to evaluate the effect of switching out micro-scale perspectives that operate within a larger macro-scale context.

Figure 11 User interface screenshot from prototype framework that allows multiple scaled models of adversarial behaviour to be docked (see online version for colours)

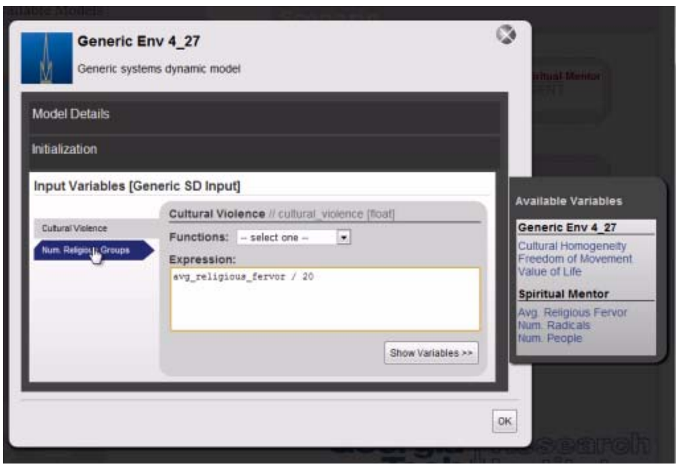
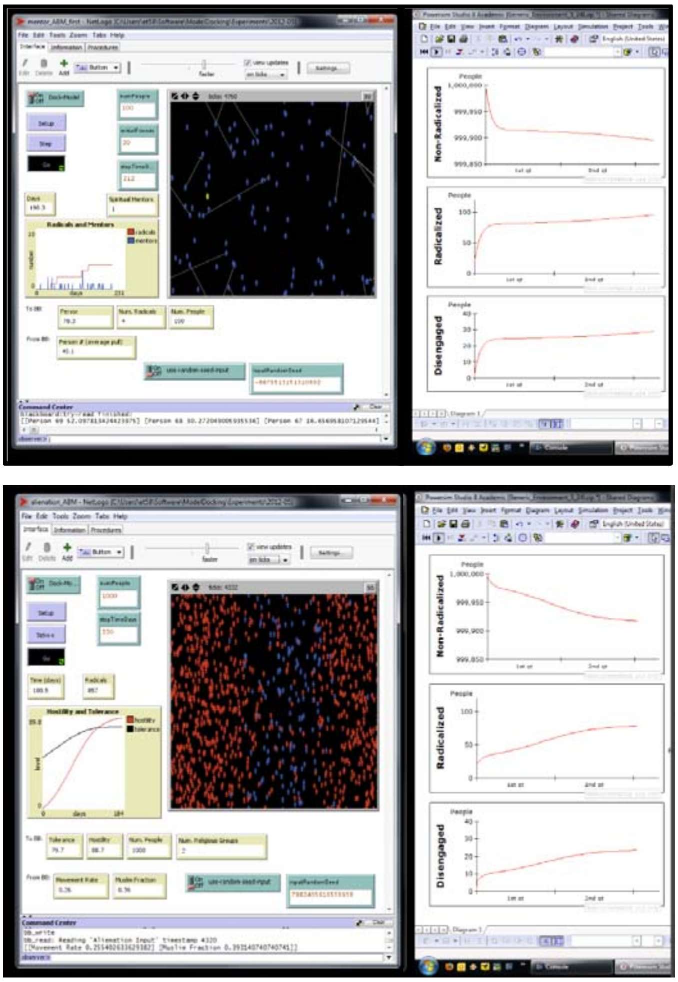


Figure 12 Screenshots of output from prototype docking framework (see online version for colours)



Notes: Top figure depicts radicalisation rates resulting from the implementation of the 'spiritual mentor' influence perspective within the macro-scale radicalisation model. The bottom figure presents results from the 'alienation' perspective integrated with the same macro-scale model as the top figure.

8 Conclusions

There are many models, formal and informal, that attempt to make sense of the complex process of radicalisation and recruitment to violent extremism. These models are often competing, presenting different views and focusing or highlighting different aspects of what is presumably the same process or variations of the same process. These models of differing views are useful in that they allow analysts to consider the problem from different perspectives. At present, many models attempting to conceptualise these dynamics tend to be limited with respect to integrating and assessing multiple qualitative perspectives into computational models. If properly developed, computational models may be valuable in that they provide a means to analyse and experiment with differing views, opinions, and perspectives of potential influences on population behaviour. This research expands a modelling construct to support computational analysis of such diverse perspectives and views associated with influences on those who may become involved with or who are already engaged in adversarial behaviour.

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