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Summary

An integrated assessment (IA) model combines knowledge from very different disciplines in view of a practical problem. Most models developed so far are rather monolithic in the sense that it is difficult to combine components from different models for purposes of new assessments. We propose to develop a modular approach to IA based on advances in knowledge management as well as in object oriented software engineering. The incentive structure of modular IA is based on turning the knowledge produced neither into public nor into private, but rather into club goods. Competition amongst modelers becomes a process of discovery at the level of module design and module coupling, with strong synergies between competing teams. Together they develop a community pool of IAM-modules, along with software and know-how for running them in varying combinations.

Keywords: Modular Integrated Assessment, knowledge management, decision support

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1. Integrated Assessment Models[1]

Integrated assessment has been defined as a process of combining, interpreting, and communicating knowledge from diverse scientific disciplines in such a way that the whole set of cause-effect interactions of a problem can be evaluated from a synoptic perspective with two characteristics (Rotmans and van Asselt, 1996):

- It should have added value compared to single disciplinary oriented assessment.
- It should provide useful information to decision-makers.

The history of the rather young scientific subject of integrated assessment is outlined in Rotmans and Dowlatabadi (1998, see also Weyant et al., 1996; Hourcade, 1997). A paradigmatic example of IA is given by the development and use of the RAINS model in the context of international negotiations about acid rain (Alcamo, 1990).

While there are different methods of integrated assessment, including expert panels, policy exercises, IA-focus groups and others (Kasemir et al, 2002), a key method consists in developing computer-based integrated assessment models (IAMs). These are powerful tools that can be used to analyze the behavior of complex systems in relation to human decision-making.

Schneider (1997) offers a comprehensive and critical survey of IAMs applied to global climate change. Models for the integrated assessment of climate change and related policies may generally be placed in one of the following categories of modelling approaches (IPCC, 1996):

- policy evaluation models
- policy optimization models
- policy guidance models.

Policy evaluation models (cf. Alcamo, 1994; Alcamo et al., 1998; Edmonds et al., 1994; Rotmans et al., 1994; Morita et al., 1994) simulate the physical, ecological and social consequences of pre-defined policies, policy optimisation models try to identify welfare maximizing policies either by cost-benefit analyses or cost-effectiveness-analyses

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(Hasselmann et al., 1997; Nordhaus and Yang, 1996; Manne et al., 1995; Richels and Edmonds, 1995; Grubb et al., 1995; Tol, 1995; Kolstad, 1994), and policy guidance models are designed to determine the entire set of climate protection paths compatible with pre-defined guard-rails (Alcamo and Kreilemann, 1996; Toth et al., 1998, Yohe, 1997, Petschel-Held, et al, 1999).

2. The pioneering phase of IA modeling

Presently, the typical IAM is a more or less monolithic model in which different components (sub-models) are strongly interlinked with each other. The model represents a dynamical system characterized by a list of real numbers (the variables), a list of functions for their dynamics (the laws of motion), and an array of exogenous parameters (usually including a description of the initial state). Often even variables that determine key dynamics of the systems in question are treated exogenously, as with technical change within the economic system. Few attempts exist to model endogenous technical change (e.g., Carraro and Galeotti, 1996). So far, IAMs are also rather weak on uncertainty representation. There are exceptions, however, where the variables are associated with probability distributions (Dowlatabadi, 1993; Hope et al., 1993). Sometimes the laws of motion include control variables. The model then computes their trajectories so as to optimize a goal functional depending on the overall systems dynamics (Nordhaus, 1994, Hasselmann, et al. 1997, Toth et al. 2002).

In general, all components are programmed in the same programming language, with overall software development tightly managed within a single institution, often by a single individual. In the pioneering days of IA-modelling, this was the only way forward. Only so could one meet the considerable conceptual and practical challenges of pulling together heterogeneous knowledge in a new kind of models. A well-known example might be the IMAGE model (Alcamo, 1994) which embodied almost 100 person-years of research and development.

There was a price to be paid, however, for these achievements. The currencies in which it had to be paid were:

- expansibility
- transparency
- applicability
- credibility.

The problems of *expansibility* are due to the fact that traditional IAMs are expanded by interfering with the existing code. This makes the enhancement of an existing IAM a cumbersome process. And as soon as an IAM involves more code than can be handled by a single individual, enhancing an existing IAM can lead to considerable management difficulties, too. Moreover, it is rather difficult for other researchers or research groups to integrate their own particular models of specific causal links into an existing IAM. This basically limits the expandibility of IAMs to the knowledge capacity of a single research group. Of course, a model can be used and sometimes enhanced by other researchers, but only if they adhere to the many features of the problem hard-wired in the original model architecture.

The problems of *transparency* result in the first instance from the high degree of interconnectedness between model components and the conventional – usually procedural – programming style. They are amplified by the widespread neglect of algorithmic clarity in software development. Often only the developers of a model know what is in the model code, and even they may have only sketchy knowledge about things like numerical stability, algorithmic complexity, domains of convergence, and the like. Model documentation is poor for a whole range of reasons, notably because developers of IAMs are in the first instance scientists and not software engineers, but including also understandable attempts to secure informal property rights where formal ones are hard to establish. For the same resons user interfaces of IAMs usually leave room for improvement. At the other end, on the side of the model users, there is a lack of training needed to penetrate and understand model code and model documentation.

Where models look simple at first sight, it is usually impossible to tell on the basis of existing documentation whether the model gives a simple representation of a complex phenomenon (the holy grail of modeling) or whether it simply misses key features of the phenomenon (the curse of modeling). With economic models, this problem is aggravated because often no clear distinction is made between prognostic and diagnostic variables. In many computable general equilibrium models, e.g., a large set of variables (the diagnostic ones) – including quantities traded and their relative prices – is computed on the basis of simultaneous variables, while only a few variables (the prognostic ones) – sometimes only a generic capital good – are computed on the basis of truly dynamic relations. While the number of diagnostic variables then can be quite high, the number of prognostic variables is actually very low. In fact, most statements about the dynamics of economic systems (e.g. the equality of rate of interest and marginal product of capital) describe features of one-dimensional systems, i.e. systems with one prognostic variable. However, this is rarely even noticed in the description of models involving such features. The emphasis on the distinction between prognostic and diagnostic variables by climate modelers and its neglect by some other modeling communities makes integrated assessment modeling even more cumbersome than it needs to be.

The lack of transparency obviously hampers the dispersion and application of IAMs and hence limits their usefulness for policy decision support (Parson, 1995). This fate is the more likely the more complex (and actually more realistic) the IAM becomes. The problems of *applicability* are intertwined with those of expandability. An application context for an IAM is a decision problem of considerable complexity (otherwise no IAM would be needed in the first place). Any such decision problem has specific features that matter a lot and other ones that matter less. Of course, one would like a model with considerable resolution and accuracy for the former and perhaps only a sketchy representation for the latter – after all, the point of a model is to simplify things (reduce complexity) with regard to some criterion of relevance. As a result, one would like to tailor existing IAMs to some extent so as to match the peculiarities of the given decision situation. But this leads into the difficulties of expandability. Moreover, one would like to have a sound understanding of the strengths and weaknesses of a given model – and this leads into the difficulties of transparency.

Finally, there is the problem of *credibility*. The difficulties of expandability mean that IAMs fail to incorporate available specialist knowledge, and this of course lowers the credibility of the IAM with the relevant specialists. What is worse, the difficulties of transparency mean that cumulative progress is rare in IAM development – models , even specific model features, are difficult to compare, and the consequences of using some feature of one IAM in developing another one usually are rather unclear.

The difficulties of applicability mean that the track record of IAMs as decision-support tools is not as strong as it probably should and could be. The strength of IAMs could lie in the possibility to produce assessments on a case-to-case basis, be it at the level of strategic decisions, regulation design, or implementation. As Hanemann and Keeler (1996, p.8) argue: "there is a definite value to allowing discretion in the regulatory process – tailoring regulations to individual circumstance and the implementation or enforcement level. Discretion has value because regulations need to be kept reasonably simple, because information is always incomplete when regulations are written, because regulatory capacity is limited, and because novel circumstances will always occur." IAMs will be useful for decision making to the extent they can be tailored to these novel circumstances that will always occur.

Given the complexities they are meant to represent, however, IAMs can hardly be credible without sound ways of representing uncertainty (e.g., Ha-Duong et al., 1997). But the key uncertainties in IAMs are neither about the size of various parameters nor about specific stochastic processes, they are about model structure. To represent these uncertainties well requires a capability to deal with subjective probabilities and to enhance them through systematic comparisons between different model structures. For this purpose, the software architecture must be flexible enough to accommodate different model structures in a transparent and expandable way.

3. Consolidation via Modularisation

Recent advances in software engineering and in the management of learning organizations provide remarkable opportunities to solve the problems that arose in the pioneering phase of IA modeling. After all, there is considerable overlap between these problems and the challenges encountered in many fields of software development over the last decades. Anybody with experience in software development is aware of the "mythical man month" – the surreal quality of time budgets for large software projects. Nor are problems of software documentation restricted to the world of IAMs – there is a sad familiarity of situations where vital knowledge about a software project is missing because a key software developer has left the organization. The answer that software engineers have developed to meet these challenges is object oriented programming (OOP, see Hill, 1996). OOP is not primarily a grammatical feature of programming languages, it is a strategy for managing the development of knowledge in computer-assisted projects.

The first side of the object oriented coin is about knowledge and human beings, while the flip side is about computers and Turing machines. As for the human dimension, the point is the establishment of well-defined accountability relations between the people engaged in knowledge development. Consider two research groups engaged in an integrated assessment, group 1 studying climate dynamics, group 2 studying economic phenomena. In a typical IAM context, group 1 might like to get from group 2 emissions trajectories for key greenhouse gases over the next 200 years in order to simulate possible climate dynamics. Group 2 in turn might be interested in the marginal effect of emissions in a given period on global mean temperature change over the next 50 years, in order to optimise conceivable policy instruments. Clearly, some agreement has to be negotiated so as to make the various expectations match. The profile of the respective inputs and outputs has to be defined: What precise features shall the output of each group have, including time horizon, time step, perhaps some uncertainty measure, certainly a clear definition of variables, etc.

Notice that the output of each group may be conditional on the output of the other one – in the example of the previous paragraph, this situation certainly arises if economic dynamics depends on a policy design based on marginal impacts of emissions. In such cases, a baseline to start with must be negotiated, as must some iteration procedure and a stopping rule.

The key point is to establish a clear distinction between the internal structure of a knowledge domain and its interface with other domains. Commitments and accountability between the research groups refer to the interfaces. The internal structure of their respective knowledge domains is their own business – from the point of view of the assessment in question, they can change it as much as they like as long as they stick to the commitments concerning the interface. Of course, these commitments can change, too, but this can only happen as a result of debates and negotiations leading to a new agreement.

We will come back to some implications of this approach in the final section, but now it is time to look at the computing side of the object oriented coin. For this purpose, it is important to keep in mind a basic property of Turing machines – i.e. the mathematical structure embodied in computers. All non-trivial Turing machines can be decomposed in smaller machines, ultimately in elementary machines performing just one step, like writing one character of the machine alphabet on a field of the machine tape. In other words, algorithms are the stuff algorithms are made of. For a complex machine, there are many possible decompositions, all equivalent in the sense that they transform the same input into the same output by performing the same steps. Moreover, Turing machines may be equivalent in the sense that they transform the same input into the same output while being different in the sense that they perform different steps while doing so.

Usually, an IAM evolves over time. It is then useful to think about a sequence of Turing machines, each of which is closely related to its predecessor in a variety of ways (in particular, the sequence may branch into different versions, and these may merge again later on). The sequence as a whole can then be decomposed in sub-sequences of smaller Turing machines. Does it matter how this is done? This is a key question in managing software development. Experience has shown that the ability to design the overall sequence of Turing machines so as to decompose it in reasonably self-contained sub-sequences is essential for productive software development involving many different people. This insight has led to object oriented programming, and it can help to develop a modular approach to integrated assessment.

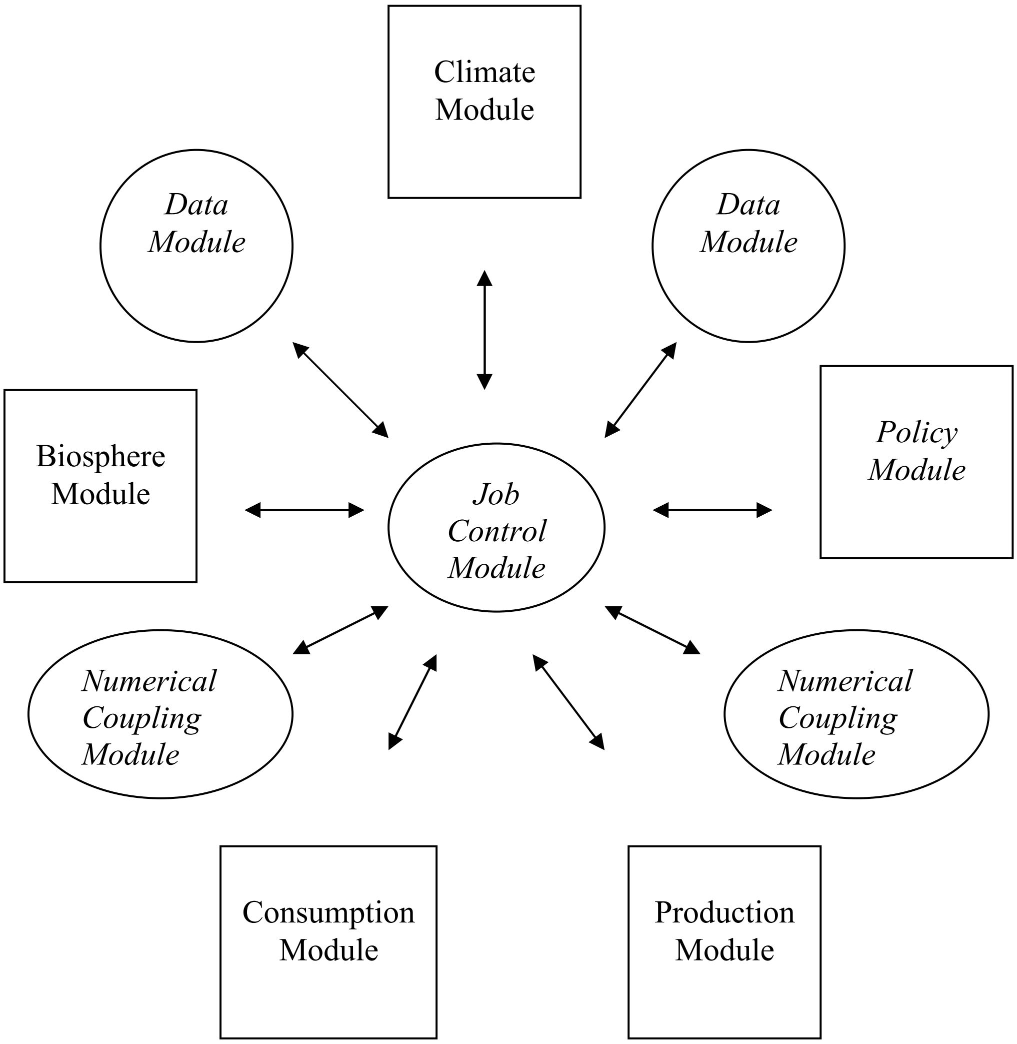

Fig. 1: Example of modular structure

Over the past decades, powerful tools for object oriented programming have been developed. They are based on combining clear commitments at the interfaces between different software objects with great flexibility in developing their internal structure. Software architecture and the grammar of programming languages have evolved accordingly. For IAMs, this provides the opportunity to move from the pioneering phase to a consolidation of this exciting line of research. First software tools for data transfer between different modules have been developed at the Potsdam Institute for Climate Impact Research (see www.pik-potsdam.de/~linstead/).

As a result of such consolidation, the field of integrated assessment will appear less as a small set of individual IA models, each leading to conclusions which depend more on the general structure of the model than the specific problem to be assessed, and more as a rapidly growing set of assessments, each based on a specific combination of modules. The robustness of conclusions can then more easily be gauged by comparisons used to check the degree to which they depend on a peculiar model structure Moreover, the logic of a specific assessment can be tailored to the needs of the decision-makers involved.

What then are criteria for a good definition of modules and their interfaces? Consider the example of figure 1, which depicts a typical situation that may arise in assessing climate policies. Five broad sets of criteria need to be considered when establishing such a structure:
1) Domains of expertise: It is often sensible to define modules so as to match existing domains of expertise, even if these domains are due to historical reasons that have little to do with the problem at hand. Domains of expertise take decades to evolve, from the point of view of a specific assessment they are in general simply given.
2) Interdependence in the phenomena to be represented for a specific assessment: Solar radiation and changes in temperature are more closely related than solar radiation and changes in stock-markets. In the climate system (including solar radiation and temperature changes) as in stock-markets, we can identify robust patterns, while the relation between the two shows hardly any clear-cut pattern. Such patterns are an important, but not the only criterion for module definition.
3) Degree of resolution needed: When dealing with, say, climate policy, one will be more interested in the energy sector than in organized crime. Accordingly, the former may be represented by a specific module while the latter is buried in aggregate economic activities. This applies to spatial and temporal resolution as much as to sectoral resolution.
4) Numerical efficiency and accuracy: Computer models are based on numerical computations with a finite set of numbers. Computing time depends critically on software architecture, and so does numerical accuracy. Clearly, a module design must take these effects into account.
5) Contingent factors: Software development depends on the availability of money and other resources, in particular skilled people, specific hard- and software, as well as the reputation needed to attract additional resources. While modelers often feel that they should hide these considerations, good management shows in the ability to balance them with the other criteria discussed above.

Clearly, this list of criteria leads to a somewhat different picture than the familiar way of asking how the system under consideration can be structured in sub-systems. In some areas, the results are the same, but with the modular approach key modules do not represent subsystems in the modelled domain at all. In particular, specific modules are often required to handle the numerical coupling between other modules. This has the advantage of making explicit the far-reaching choices that are always involved in the selection and design of algorithms. But even without this advantage, modules for numerical coupling are simply unavoidable for any modular IAM with non-trivial dynamics.

A key feature of figure 1 is the star-topology of the software. Modules do not talk to each other, they talk to the job control module via standardized input and output files. How to do this well is likely to become an important part of the art of building IAMs. The use of standardized input and output files means that different programming languages can be combined, as it is sufficient to implement a GET and a PUT operation in each one of them in such a way as to meet the standard for files to be used at the interfaces. Moreover, and this is critical, the job control module does not constrain model structure. The star topology provides a clearing house for inputs and outputs, not a definition of how the problem at hand is to be structured and solved.

The latter distinction provides the key to enhancing expandability and transparency as discussed in section 2. Once an interface is defined for a module by specifying what the module gets from and gives to the job control module, one can replace the current module which represents an instance of the respective generic module by another module as long as it fits the requirements of the interface. More complex topologies may be useful later on, but they need to preserve this basic feature of modular IA.

The star-topology can, of course, imply a considerable overhead of the job control module that links the different modules with each other. The linkage should be achieved, ideally, independently of the programming language in which the different modules are coded. Whether or not the overhead of translating between different codes (which may well have fundamentally different internal data structures) is acceptable, will depend critically on the amount of data that is transferred between individual modules, compared with the amount of number crunching that is performed within the modules between data transfers (a familiar problem from the optimisation of codes for parallel computers). For example, the linkage of different modules whose coupled time trajectories are to be optimised according to a given criterion can involve major data transfer rates and may require the agreement on a common programming language for different modules. This holds particularly when the programming language for one module (e.g. the economic system) is a meta-language such as GAMS, while another module (e.g. the climate system) is programmed in C++ and, say, a special Fortran adjoint model compiler is applied for optimisation.

The question of the optimal modular structure of the model hierarchy and the degree of permissible freedom in the coding languages used for different modules will need to be carefully analysed. It may well be that in addition to strict conventions for the data interfaces, some general agreement on design patterns and forms of encoding used for the individual modules would be quite productive. Only experience can show whether design tools like the unified modeling language (Booch et al., 1999) will be helpful or just an additional burden. The numerical mathematics and the management problems involved in these issues are so complex that they cannot be settled a priori, they rather call for a steady process of learning by doing in modular modeling.

4. Challenges on the Road

It is interesting to look at the development of IAMs as an instance of knowledge management. From an economic point of view, scientific knowledge is often considered as an instance of a pure public good. The problem then is to provide a set of incentives to avoid underproduction of such knowledge, e.g. by establishing intellectual property rights via patents or by gearing the production of knowledge to non-transferable scientific reputation of organizations and individuals. The difficulties of managing software development are instructive among other things because, at first sight, algorithms look like perfect instances of public goods. Given a car, it is still a lot of work to produce a next one; given a program, the costs for copying it are usually negligible in comparison with the costs of its development. The incentive structure of object oriented programming, however, is based on turning the software objects neither into public nor into private, but rather into club goods. With regard to IAMs, this means developing a community pool of IAM-modules, together with a software for running them in varying combinations.

The objects we are dealing with here are not simply chunks of software, they are knowledge modules. Since the days of Plato, the relationship between mathematical entities and other domains of discourse has kept philosophers busy. The least one can say is that this relationship is more subtle than one may think at first sight. From a practical point of view, the main point is that a knowledge module is much more than an algorithm. It is an algorithm implemented in a specific way, combined with specific data, interpreted in a context of non-mathematical realities and before a background of implicit knowledge. In order to use a knowledge module, then, one must have access to a suitable environment not only of hardware and software, but also of experience and understanding. This environment is a resource jointly produced by a social network of professional specialists, it is a club good of that network.

This of course raises the problem of abuse: A given module may be implemented without the appropriate background and context, leading to false results that may be hard to recognize as such by outsiders. It would be utterly naïve to deny that danger, but it would be similarly naïve to attribute it to the modular approach. Abuse of scientific knowledge is a core problem of science as a human activity, and it arises with modular approach to integrated assessment, too.

The problem has two sides. On the one hand, there are many instances of scientific knowledge being used for problematic or plainly evil purposes so as to yield terrible consequences. In the domain of global environmental change, this problem is not yet very acute, but things may change with progress in geo-engineering. On the other hand there is the issue of scientific knowledge leading to false conclusions because it is used out of context. Classical examples include risk assessments based on laboratory conditions but applied in "real world" situations. Another example is provided by widespread ambiguities between apocalyptic visions of environmental catastrophes and descriptions of worrying, but much less catastrophic, global environmental phenomena. Of course, the two forms of abuse can be and often are combined.

These problems cannot be avoided, but they can be solved. A modular approach to integrated assessment makes their solution easier, not harder, for two reasons. First, the increased transparency makes it easier to detect problems of abuse. And second, the mobilization of more diverse networks of expertise makes it easier to develop suitable forms of quality control. However, appropriate forms of quality control will not emerge by doing nothing. To get them will take years of disciplined research in which experts from different fields develop a joint practice of reviewing the use of specialised modules in integrated assessments, while experts in management science and related fields develop a complementary practice of reviewing the use of integrated models in actual decision making. The only way of developing suitable forms of quality control is by developing modules, using them for integrated assessments, and exposing this process to on-going review and reflection.

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