System Dynamics and Decision-Making in the Context of Dynamically Complex Multi-Dimensional Societal Issues

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Abstract

Dynamically complex multi-dimensional societal issues are societal issues characterised by complex time evolutionary behaviour on multiple dimensions, and very often also by many uncertainties, multiple views and parties concerned, and different ethical aspects. It will be argued here that stand-alone system dynamics often needs to be complemented with other methodologies or disciplines –for example multiple criteria decision analysis and/or ethics– in order to support the selection of appropriate strategies when dealing with such issues. This paper looks at the combination of system dynamics, multiple criteria decision analysis and ethics to support strategy selection in case of such dynamically complex multi-dimensional societal issues, with special attention paid to the capacity of the multi-methodology to deal with multiple dimensions, multiple time scales, multiple parties and views, uncertainty and ethical aspects.

Keywords: Dynamic Complexity, Multiple Dimensions, Multiple Time Scales, Multiple Parties and Views, Ethics

1 Introduction

This paper is part of a broader research project with the overall goal to develop and apply consistent methodological matches of system dynamics, multiple criteria decision analysis and ethics to deal with two interrelated dynamically complex multi-dimensional societal issues (DCMDS issues), namely the transition towards sustainable energy systems and climate change. In this paper, the potentiality of system dynamics for decision-making in the case of such DCMDS issues will be looked at.

In section 2, the problem will be stated and a potentially interesting solution suggested. In subsection 2.1, it will be explained what is meant by *dynamically complex multi-dimensional societal issues*. Then, the use of stand-alone system dynamics to deal with such DCMDS issues will be discussed in subsection 2.2. From this discussion, it becomes clear that system dynamics is mostly necessary but not sufficient –in stand-alone mode– to deal with such issues. This will be illustrated by means of a simplified example from the work on energy systems and climate change in subsection 2.3.

In order to make system dynamics appropriate for supporting strategy selection in such cases, the combination of system dynamics, discontinuous multiple criteria decision analysis methods and ethics will be proposed and looked at in section 3. There, the contribution of the proposed multi-methodology for dealing with dynamic complexity, multiple dimensions, multiple decision-makers, stakeholders and parties (with different views), multiple time scales, uncertainty, robustness and resilience will be briefly discussed. In subsection 3.7, these extensions will be applied to the example discussed in subsection 2.3.

And finally, some conclusions will be drawn in section 4.

2 Dynamically Complex Multi-Dimensional Societal Issues and System Dynamics

2.1 Dynamically Complex Multi-Dimensional Societal Issues

Many *societal* issues are *dynamically complex* and *multi-dimensional. Dynamically complex* means that the time evolutionary behaviour is complex. Dynamic complexity already arises in quite simple systems by delayed influences, non-linear interactions between different elements, et cetera.

Multi-dimensional refers to the multiple aspects of the same issue by which it could be characterised such as aspects of profitability or pollution, which could be bundled into broader dimensions like the economic dimension, the environmental dimension, the social dimension and the cultural dimension. It should be clear that issues are mostly not static and uni-dimensional, but still, this paper deals with issues that are *particularly* characterised by multiple dimensions and dynamic complexity. This complex behaviour on multiple dimensions over time complicates strategy selection, especially when there is not a single obviously best strategy on all dimensions over time (see subsection 2.3 for an example), which is mostly the case.

Issues are called *societal* if they impact society and/or if society impacts them. This often means that multiple decision-makers, stakeholders, stakeseekers, other agents and impacted parties on different time and geographical scales –all with their own views, goals, interests and preferences– are somehow involved or impacted which further complicates decision-making.

Moreover, such issues are often characterised by many uncertainties and risks, high degrees of urgency, high degrees of persistence, by the dynamics of the broader context/transitions or related issues and domains, the involvement of several decision-makers with divergent (non-convergent) views, impacting directly and indirectly many current and future stakeholders and third parties on multiple time and geographical scales, by disequilibria, imperfect information/ asymmetries, bounded rationality, et cetera.

At first sight, the overwhelming complexity of such DCMDS issues seems to make good decision-making in such cases almost impossible, especially when taking into account the fact that unassisted human beings cannot consistently infer the behaviour of dynamically complex systems and cannot deal simultaneously with more than seven aspects, not to mention decision-making taking into account many strategies which impact many dimensions over time in very different ways depending on the perspectives and associated underlying structures as in the case of these issues. But still, many DCMDS issues are of the utmost importance and require timely, informed and justifiable decisions to be made and strategies to be selected and implemented. This paper focusses on model-assisted strategy selection in case of such DCMDS issues.

2.2 Strengths and Weaknesses of Stand-Alone System Dynamics for Dealing with Dynamically Complex Multi-Dimensional Societal Issues

System dynamics seems particularly interesting for dealing with the *dynamic complexity* of such DCMDS issues *if* underlying causal relationships can be observed, assumed or constructed[1]. So,

[1]For system dynamics to be of any use, it is not necessarily required that the decision-makers and/or stakeholders agree on the important dimensions, on the causal structure or the resulting dynamics over time. What is required though is that causal relationships could be perceived/described. Then system dynamics could be used to explore the interaction between the structure and the dynamically complex behaviour of these issues in a holistic way in order to gain insight, and from this increased insight, transform the structure/behaviour appropriately. This stress is rather important because it means that a *structural systems* perspective is implicitly adopted and that structural (dis)solutions are looked for. The hypothesis behind this structural view is the system dynamics assumption that the (feedback) structure of a system generates its behaviour.

system dynamics allows the simulation of strategies *over time* in such a way that the behaviour of the model unfolds continuously over time, from the very short term to the very long term (depending on the time horizon chosen).

System dynamics is also fundamentally *multi-dimensional*, considering the most important long-term consequences including their economic, environmental, social, cultural, moral and other implications, without attaching more importance to one of these dimensions. Moreover, non-monetary dimensions are not transformed into monetary ones if this is not in accordance with reality[2].

Other reasons to use system dynamics models for strategic decision-making in case of DCMDS issues are that they allow to deal with holistic perspectives, feedback effects, explicit representations of accumulations, delays, disequilibrium dynamics, endogenous (technological and social) change, uncertainties, subjective/soft elements, rationally bounded decision rules, strategic thinking, and contexts without historic precedents and data. So, system dynamics supports dealing with the (perceived, assumed or constructed) time evolutionary behaviour of (perceived, assumed or constructed) structures on multiple dimensions, and is appropriate for simulating the dynamic complexity of DCMDS issues.

But *stand-alone* use of system dynamics for decision-making in case of such issues also shows several shortcomings. First, *stand-alone* use of system dynamics does not automatically answer the questions as to *what* views, dimensions and time frames really matter and ought to be included/evaluated. Second, it does not really tell *how* to take multiple (conflicting) views and multiple dimensions over time into account. It therefore does not not tell how to select a strategy when no strategy is best and most robust at any time on all dimensions for all parties given all uncertainties. This will be illustrated by means of an example in subsection 2.3. Third, it does not allow the consideration/integration in the strategy selection of many other types of information (mostly qualitative) concerning robustness, uncertainties, et cetera. So, stand-alone use of system dynamics is less appropriate for evaluation and choice when the strategy selection is not obvious/unambiguous.

2.3 Example of a DCMDS Issue

A good example of non-obvious strategy selection in case of a DCMDS issue is the selection of a strategy to stimulate the development of a sustainable EU25 energy/electricity system. Any major strategy in this domain has important consequences on multiple dimensions such as the economic dimension (e.g. the total investment cost of total generation capacity), the social dimension (e.g. electricity consumption prices), the environmental dimension (e.g. CO_2 emissions), the technical dimension (e.g. stimulating different technological development paths), et cetera. These strategies also impact these dimensions on multiple time scales –ranging from the very short term (say next year) to the very long term (say after 2100)– and that in very different ways. Moreover, there are many uncertainties and risks involved. And different parties have very different perspectives on the energy/climate change issues.

Figures 1 to 4 show the time evolutionary behaviour of only three (of dozens of important) aspects of only three (out of many hundreds of) strategies simulated in case of only one scenario in one structural setting of a recently developed system dynamics model built to explore the diffusion of CO_2-poor energy technologies in the EU25 electricity system in order to cut CO_2 emissions. The dynamics of the system dynamics model is driven by endogenous technological change. Other structural variants, scenarios, strategies and uncertainties are not dealt with here for reasons of ease of explanation.

The three policy sets shown here are a base case (BC) without any climate change policies imposed on the electricity sector, a set of strong climate change policies (POL2) and a set of extremely heavy climate change policies (POL3)[3]. The scenario simulated here is the HYDRO-

[2]See for example (Sterman 2002, p505), (Meadows and Robinson 2002, p298) and (Forrester 1994, p251).

[3]The POL2 policy set is actually much stronger than the set in place today or currently under consideration, and the POL3 policy set is even harder, probably too hard to be politically acceptable.

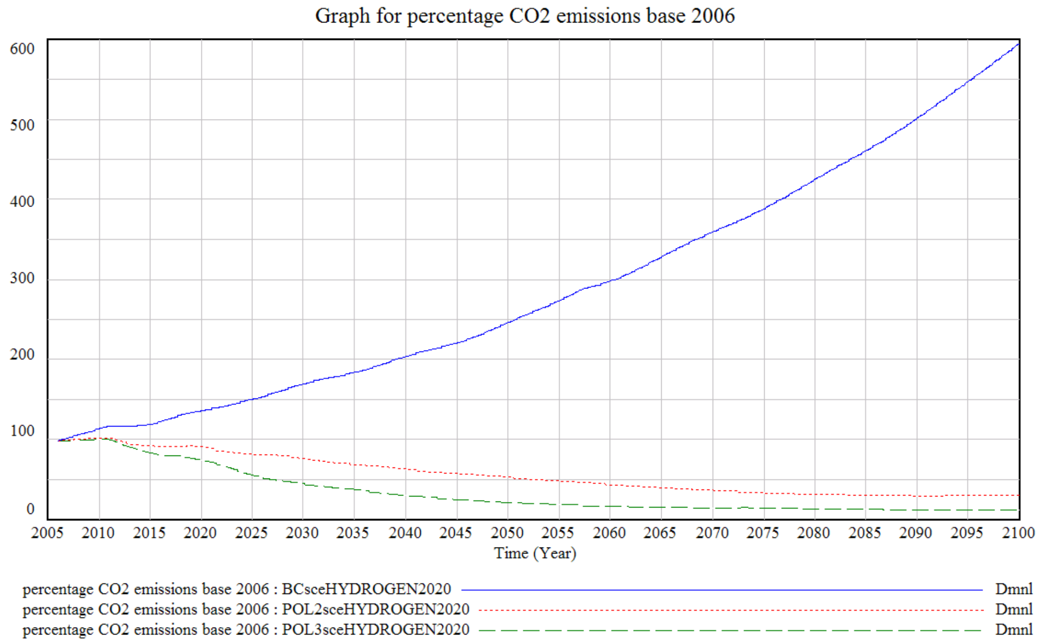


Figure 1: Criterion f_1: Evolution of the CO_2 emissions of the three policy sets between 2006 and 2100 as percentage of the 2006 CO_2 emissions

GEN2020 scenario in which hydrogen becomes a technically feasible energy storage medium to accommodate intermittent supply (and to some extent also variable demand) *without* generating additional electricity demand caused by a transition to a coupled electricity-'hydrogen economy'.

Figure 1 shows the model-generated evolution of the total EU25 CO_2 emissions between 2006 and 2100 as a percentage of 2006 emissions. In the BC, CO_2 emissions rise to about 2.5 times the 2006 emissions by 2050 and about 6 times the 2006 emissions by 2100. The strong climate change policy set POL2 leads to marginally lower CO_2 emissions until the year 2020 from which moment on a steady decline sets in, resulting in a reduction of CO_2 emissions of 50% by 2050 and 70% by 2100. And in case of the extremely strong policy set POL3, the steady decrease starts just after 2012 leading to reductions of 80% by 2050 and 90% by 2100. On this aspect of the environmental dimension, POL3 and POL2 are at any moment in time unambiguously preferable to the BC policy set.

However, the opposite is true for the aspect 'electricity consumer prices' which is an important aspect of the economic and social dimensions. Figure 2 shows that electricity prices slightly decrease in the BC but gradually increase to more than 2 and almost 4 times the 2006 price by the year 2100 in case of POL2 and POL3 respectively. Hence, the BC is clearly preferable at any time over POL2 and POL3 on this aspect of the social dimension.

Taking (only) both these aspects into account already complicates the strategy choice, because there is no unambiguous best/optimal strategy on both dimensions 'dominating' the other strategies. Strategy POL2 might then even be considered an acceptable compromise strategy because it is an efficient solution (not dominated by any of the other strategies) although it is not preferred on any of the criteria.

But the strategy selection becomes even more difficult when time-evolutionary behaviour *per dimension* is ambiguous. This is the case for the aspect 'total wind power capacity installed' which is an important criterion for the wind turbine construction industry –a specific group of stakeholders with specific views, interests and goals. Figure 3 shows the same evolution until 2010 for the three policy sets, after which the BC initially shows lower installed wind power capacities than policy sets POL2 and POL3 because of a lack of mechanisms to stimulate new wind power

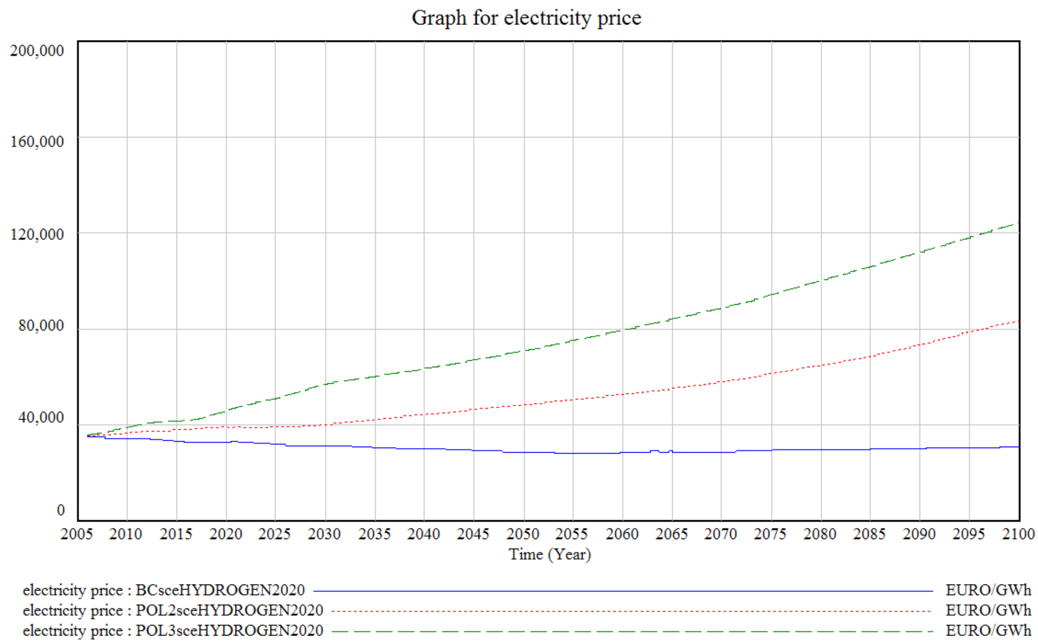


Figure 2: Criterion f_2: Evolution of electricity prices between 2006 and 2100

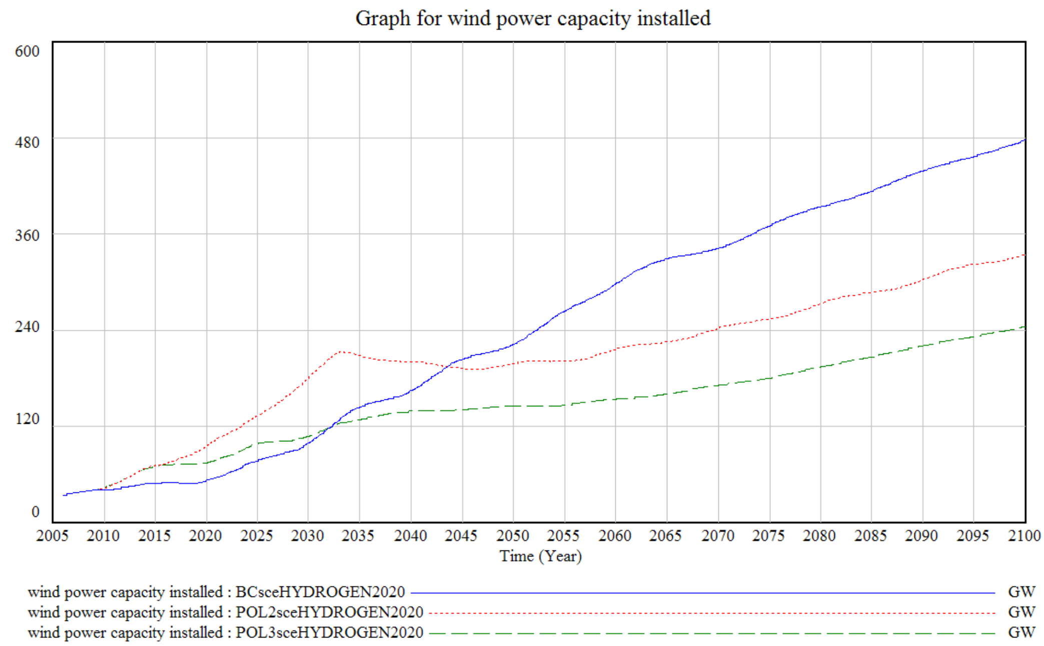


Figure 3: Criterion f_3: Evolution of the installed capacity of wind turbines between 2006 and 2100

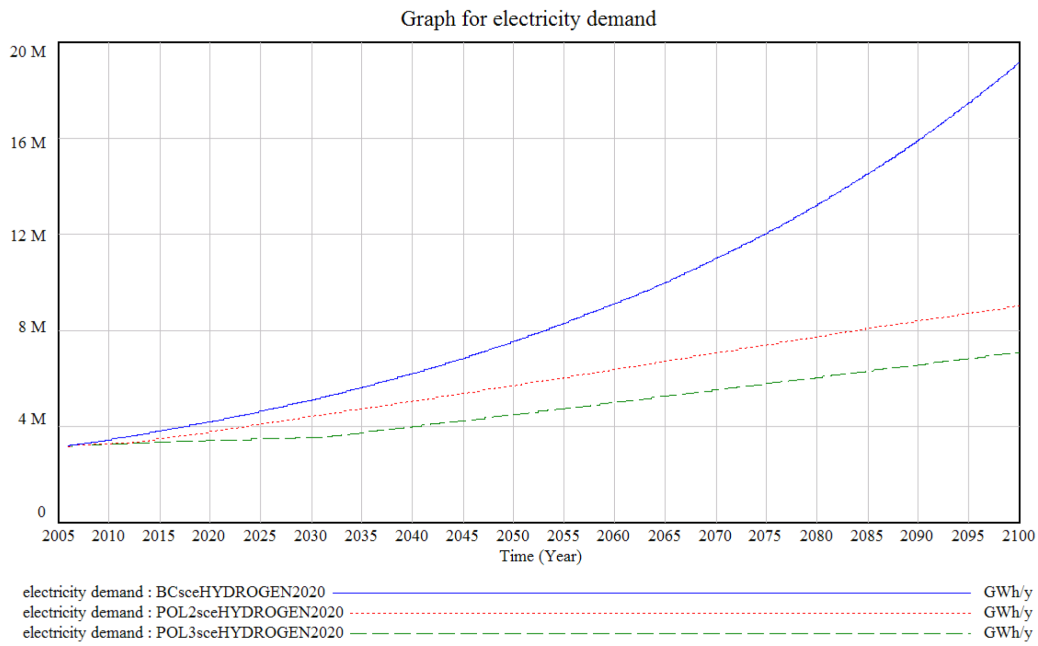


Figure 4: Evolution of the EU25 electricity demand between 2006 and 2100

capacity. After 2016, POL2 shows a higher installed capacity, until the BC catches up[4] and dominates both other strategies from the year 2043 on.

Now, if only taking this latter aspect into account and only from the point of view of the wind turbine construction industry, then which of these policy sets is preferable: the strong climate change policy set (POL2) which is most interesting in terms of wind power capacity installed until about 2043, or the BC policy set which is most interesting in the long to very long term, or the very strong climate change policy set (POL3) which leads to lower absolute –but higher relative– numbers of wind power capacity installed? The choice is not obvious: taking into account *only* the evolution on this single aspect already leads to difficulties for choosing unambiguously one of these strategies, not to mention the evolution on many (conflicting) dimensions and/or multiple (conflicting) views and/or multiple uncertainties.

Moreover, it is often also interesting to evaluate other characteristics –such as the robustness and flexibility of strategies– and other (types of) information too. This makes the strategy evaluation even more difficult.

3 System Dynamics, Multiple Criteria Decision Analysis and Ethics for Decision-Making in the Context of Multi-dimensional Dynamically Complex Societal Issues

This paper claims that the combination of system dynamics, multiple criteria decision analysis and ethics might be appropriate for strategy selection in case of DCMDS issues. Ethics could be used (i) to deal with questions as to what dimensions, views and time frames really matter –which are inevitably ethical questions and decisions to be made– and ought to be included, (ii) to eliminate 'unethical' strategies, and (iii) to embed the entire process. System dynamics could be used to simulate the multi-dimensional time-evolutionary behaviour (of different views). And multiple criteria decision analysis methods could then be used to describe, evaluate and

[4]This catch-up by the BC policy is (among else) caused by the much higher electricity demand (see figure 4).

choose –simultaneously taking multiple dimensions, multiple time scales, multiple divergent (even conflicting) views, and other aspects such as uncertainty, robustness, flexibility and resilience into account– between the strategies simulated with the system dynamics models.

However, both the domains of multiple criteria decision analysis[5] and ethics are vast[6] and characterised by many different schools. Different methods and approaches seem to be more appropriate depending on the issues and system dynamics approaches used. But even the brief discussion of both fields or the introduction of specific methods/approaches goes beyond the scope of this paper. Discrete (or multi-attribute) multiple criteria decision analysis and ethics will therefore be used in this paper in a general –non-technical– sense, just to illustrate the idea. Those interested in a technical and elaborated account are referred to (Pruyt 2006a).

The following subsections discuss how this multi-methodology might help in dealing with some important aspects of DCMDS issues, more precisely, with multiple aspects and dimensions, with multiple time scales, with multiple parties with multiple views and preferences, with uncertainties, robustness, resilience and flexibility, and with ethical aspects. A non-technical illustration is provided in subsection 3.7.

3.1 Multiple Aspects and Dimensions

The tandem system dynamics-multiple criteria decision analysis allows to deal with multiple aspects and dimensions. Multiple aspects are represented in the system dynamics model by means of stock variables (the states of the system) which could be evaluated at specific moments in time. Different co-flows allow different aspects/properties to be modelled and kept track of. And multiple criteria decision analysis integrates the different aspects and dimensions by means of multiple criteria. Different forms of aspects-criteria could be used: from quantitative to qualitative criteria, and from content criteria to criteria dealing with other characteristics. 'Robustness' criteria could for example be used to check the robustness of very long term goals with changes in the initial conditions, parameters or events. Flexibility criteria could be used to check the flexibility at different moments in time to adjust the strategy. Other criteria could evaluate the in/feasibility of strategies, such as the resistance to strategies in the (very) short and medium term. Resilience –although difficult to quantify and simulate in quantitative system dynamics models– could also be integrated in multiple criteria decision analysis models as aspects-criteria that are to be maximised, and so on. See subsections 3.4 and 3.5 for a slightly more detailed account concerning uncertainty, robustness and flexibility.

But questions as to what aspects and dimensions really matter are not answered by any of theses ideographic methodologies: they depend on the issues at hand and the meta-perspective –for example a specific ethical perspective– assumed.

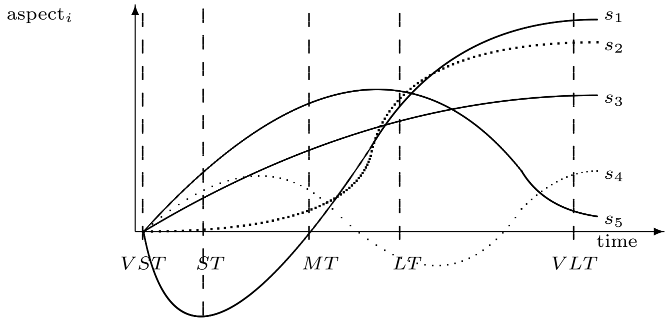
3.2 Multiple Time Scales

Decision-making taking simultaneously different aspects/dimensions into account –which is in fact a classic example of a mathematically ill-defined multiple criteria decision analysis problem– becomes even more difficult when these dimensions evolve dynamically over time. The combination of system dynamics, multiple criteria decision analysis and ethics could also help to deal with this time-aspect of DCMDS issues: system dynamics could help to simulate the *dynamics over time*, discrete multiple criteria decision analysis could help to evaluate the multiple dimensions *on different important moments in time*, and ethics could be used to determine what time perspectives and moments in time really matter.

[5]Multiple criteria decision analysis is the name adopted by the community developing (mathematical) models to aid decision-makers decide, taking simultaneously multiple (conflicting) dimensions ('criteria') into account. See (Figueira, Greco, and Ehrgott 2005) for a broad introduction to some of the many multiple criteria decision analysis methods.

[6]The vastness of these domains may be a practical problem for system dynamics practitioners interested in consistently combining all three of them.

Figure 5: Example of the time problem on a single dimension



However, practically combining continuous system dynamics and multiple criteria decision analysis leads to a specific problem, which will be called the '*time problem*' and which was already hinted at in the example discussed in the previous section.

The 'time problem' will be illustrated here with a hypothetical example using purely quantitative trajectories for ease of explanation and visualisation (more qualitative scales and interpretations are also possible). Figure 5 shows simulated trajectories of 5 different strategies on a single aspect/criterion to deal with one and the same issue. Now, which strategy will be chosen? Curve s_1 appears to be the best in the *very long term* (VLT), but extremely bad in the *short term* (ST). Curve s_2 seems to be somewhat less interesting than s_1 in the *very long term*, but does not show a negative evolution in the *short term*. Curves s_3 and s_5 promise even better result in the *short* and *medium term* (MT), but are projected to be worse to extremely worse in the *very long term*. And strategy s_4 seems to result in cyclic behaviour over time. Now, when considering complex time dynamics contained in decisions –even on only one aspect– it is mostly not possible any more to unambiguously choose the best strategy, not even in the purely quantitative case discussed here.

Several ways to deal with this 'time problem' could be proposed such as:

1. *To focus on one moment in time:* decision-makers often simplify and focus only on one moment in time e.g. sometimes the short term profitability or sometimes the *very long term* goal. In the hypothetical example, this implies choosing the fifth or the first strategy. The disadvantage of such extreme simplifications is that important information is not taken into account. In spite of its good very long term *performance*, strategy s_1 might for example be unacceptable in the short term, and strategy s_5 may be good in the medium to long term but might be unacceptable in the long term.

2. *To discount to the present:* another way of dealing with the time problem is to discount all trajectories back to the present (t_0) and compare their 'net present values'[7]. Problems of such approaches are:

   (a) the compensation between time scales: an exceptionally good short term future could for example compensate/trade-off an extremely bad long term and very long term future;

   (b) the undervaluation of the future which is discounted at a discount rate –often a social discount rate (or simply the interest rate)– which results in a (strong) time preference for the present;

   (c) the choice of the final time horizon.

[7]However, the monetarisation of all dimensions and the calculation of NPVs runs counter to everything system dynamics and multiple criteria decision analysis stand for....

3. *Integration of the trajectories:* a third route could be the integration of the continuous trajectories, which comes down to discounting with a discount rate of 0%. However, this does not take away the 'compensation' critique.

4. *Qualitative comparison of the complex dynamical behaviour:* a fourth option could be to compare the *behaviour* of the strategies over time for each dimension. Often however, this will not lead to unambiguous rankings of strategies per dimension or clear qualitative evaluations of strategies over the time span considered.

5. *Evaluation on discrete moments in time:* a fifth option could be to consider a set of discrete moments in time and treat them as criteria in a discrete multiple criteria decision analysis. A technical problem with this approach might be that the moments in time are not per definition well chosen and could therefore lead to dependence of criteria, which is considered problematic in multiple criteria decision analysis.

6. *Evaluation on specific relative moments in time:* an extension of the fifth option is to consider some very specific but relative –i.e. depending on the issue at hand– moments in time which contain very different information, to evaluate the different dimensions/aspects at these different moments in time and to treat the resulting content-time criteria as quasi-independent criteria. This is the approach elaborated here. These relative time scales are *the very short term, the short term, the medium term, the long term* and *the very long term.*

These relative time scales could be defined –depending on whether the strategy involves (i) many successive actions or (ii) just a one-shot action– as follows:

1. The *very short term* (called the short term by most system dynamicists): is the time scale (i) on which evaluations cannot tactically and/or structurally be changed, or (ii) on which the current evolution cannot be stopped. Meadows and Robinson (1985, p86) note that in system dynamics terms 'the [*very short term*] is determined for any system by the length of the dominant delays'. Most mainstream system dynamicists are not interested in this time scale because of the fact that the very short term is already determined and is therefore unchangeable by structural policies (Meadows 1980, p49).

2. The *short term*: is the time scale (i) on which tactical actions could be initiated, or (ii) in which a slight change of course could be achieved by timely decisions. This time scale gives an idea of the very near future situation depending on immediate action.

3. The *medium term*: is the time scale (i) on which structural actions could be implemented or start to bear some fruit, or (ii) in which a clearly structural change could start to take off.

4. The *long term*: is the time scale (i) on which the structural actions could bear fruit and at which moment it could be checked whether the system is really heading in the desired direction, or (ii) the structural improvement becomes clearly noticeable.

5. The *very long term*: is the time scale (i & ii) on which goals could be reached or the time dynamics of the system could fully play its part. This is a very important time scale because real structural decisions can only be made about things that can be changed. Thus, strategic decisions have to be made in the first place about changes in the *very long term*, since it is impossible to structurally change anything in the very short and the short term (as defined here). One of the most important question is therefore: what goals are desired in the very long term? These goals partly determine the *very long term.* But system dynamicists are not solely interested in goals or end-states: '[a]ttention is focused on the general system reaction to general disturbances and on the dynamic path of a response rather than its end state' (Meadows and Robinson 1985, p79). So, the other moments in time matter too, especially because they implicitly contain information about the general system response.

These moments in time are relative: the exact moment in time chosen for each relative time scale depends on the issue at hand and the dynamic responses of the system of interest to the strategies considered. Forrester (1971, p94) notes in this respect that '[s]hort run and long run must be defined in terms of the dynamic responses in the system of interest. In corporate affairs, short run might be one to three years and long run beyond five years. In urban or national issues, short run could be a decade, while long run might be twenty years or more. In world dynamics, short run is several decades, and long run is fifty years to several centuries. Policies and programs which produce long-run improvement may initially depress the behavior of a system. This is especially treacherous. The short run is more visible and more compelling. It speaks loudly for immediate attention. But a series of actions all aimed at short-run improvement can eventually burden a system with long-run depressants so severe that even heroic short-run measures no longer suffice'. So, while using the same relative time scales (such as the '*long term*'), the absolute moments in time they represent depend on the issues.

The evaluation of all important aspects at different relative moments in time seems simply to lead in multiple criteria decision analysis terms to the inclusion of new criteria. But in multiple criteria decision analysis, criteria are generally required to be independent. Now it could be argued that these time-scale criteria per aspect or dimension over time are not independent: they are dependent in time since the *very short term* leads to the *short term*, the *short term* to the *medium term*, et cetera. But it could on the other hand be argued that they are independent because of the fact that they contain information about aspects at very different moments in time *and* because of the fact that they contain *fundamentally different information*: the very long term contains for example information about the (feasible) long-term goals, the long term about the paths to the goals, the direction of changes and the timing of potentially needed corrective action, the medium term about the moment structural measures might start to work, the short term about the moment tactical measures could be introduced and the very short term about the current state of affairs which cannot be changed in any way, but which might be perceived differently and could therefore in some cases be interesting to take into account. The short term, medium and long term might also contain important indications whether a strategy will meet obstacles or resistance (which are for example not integrated in the system dynamics model) which could block the attainment of the desired goals. Hence, evaluations on these time scales might indicate whether the long term goals might actually be reached or not, or whether strategies are acceptable or not.

Now, extending the criteria with these time scales looks at first sight easy to do. And indeed, this is true for most multiple criteria decision analysis methods, at least from a technical point of view. But at second thought, it is somewhat more difficult, because it requires critical reflection about the specific information to be obtained which will in turn influence the precise form of the criteria. At first sight it also seems to lead to much more criteria, namely $(m * t)$ aspect-time scale pairs compared to only m aspects if the strategies are not evaluated over time. In practice, this turns out to be less problematic, since not all time scales and aspects are to be evaluated at all time scales. Whether a time scale should be evaluated and taken into account in the multiple criteria decision analysis depends on the issue, the information that is sought and the ethical perspective taken. Mostly this means taking into account short term, long term and very long term evaluations.

This 'time scale' proposition fits –technically speaking– well with discrete multiple criteria decision analysis methods. And this approach is not limited to quantitative trajectory evaluations at discrete moments in time as in the example used in this subsection, but could also be used for qualitative or fuzzy evaluations at these relative moments in time (such as 'the strategy is *acceptable* in the very long term' or 'is characterised by *gradual* improvement in the medium term'), for intervals or probability distributions, or for integrations over time intervals.

3.3 Multiple Parties and Views

DCMDS issues and the strategies used to dissolve them almost certainly involve –apart from clients or problem-owners, decision-makers and analysts which are traditionally involved in decision-making– many stakeholders, stakeseekers, agents, and impacted third parties with different world-views, value systems, prior knowledge, emotions, perceptions, roles, interests, goals, positions and leverage.

It seems to be important to take these different interests, positions, points of view and leverage into account on top of those of the decision-maker(s) or the problem owner(s) in order to choose more ethical –more responsible towards others especially towards (potentially) impacted third parties– and better –because anticipating possible (adverse) reactions of other parties[8]– strategies. What makes it even more difficult is that these complex issues often involve decision-makers, stakeholders and impacted parties on different geographic and time scales and different organisational/institutional levels with many inter-level interactions.

These different views are also important because of the fact that issues are almost never decided on once and for all by only a single decision-maker or without arousing reactions of other parties. Even worse, mostly there are multiple parties who can only decide on or influence parts of the system at different moments in time. Or stated differently, decisions and actions by other decision-makers and stakeholders are part of the bigger feedback loop, but are shielded of by subsystem boundaries. Not taking them, their views and their potential reactions into account could therefore be very harmful for oneself. Taking this feedback loop into account might also lead to the realisation that seemingly conflicting interests of stakeholders and stakeseekers are actually interests for the decision-makers as well, because of the fact that the decision could be negatively affected by their (re)actions.

Meadows, Richardson, and Bruckmann, (1982) state that examining issues from multiple perspectives is a central principle of system dynamics (Sterman 2000, p32), and some system dynamics practice and work does indeed deal with multiple perspectives. Still, it seems that the importance of such multiple perspectives is not emphasised enough in current system dynamics practice, nor is the usefulness of system dynamics for dealing with them and the resulting uncertainty: system dynamics theory 'rarely touches on practical means of helping participants generate and articulate a richly divergent set of significantly different views which might then inspire different issues upon which a model building study may centre' (Lane and Oliva 1998, p224). This is probably due to the underlying ontological and epistemological assumptions of mainstream system dynamics which –in case of different views– incite naturally to integrate the different views into one consensual model in view of reaching joint understanding about the one underlying real-world system to reach a consensus. However, such a consensual approach is not always appropriate. Sometimes it will be more appropriate not to try to develop a common view and to keep the divergent views apart. Both approaches are interesting and lead to different results. Whether to look for a group model or to explore different views separately depends on the issue at hand, the parties involved, their world-views, the specific context, the paradigmatic approach[9], et cetera.

Still, system thinking and system dynamics could –in case of multiple views– effectively help to:

- reduce the uncertainty about who the stakeholders and third parties really are;
- surface, structurally represent the visions and assumptions different parties have, and compare them;
- deduce the resulting system/model behaviour(s of the modelled views);
- explore and compare the different (resulting) behaviour(s of the different views);

[8]Liebl (2002, p164) argues in this respect that even dormant, dangerous, demanding,... stakeholders and stakeseekers, whether legitimate or not, whether powerful or not, are all potentially important. He points out that it is 'dangerous to ignore stakeholders who are regarded as not legitimate but who may raise considerable mobilization [and that] the acceptance of a solution by the relevant stakeholders will become a key to project success' (Liebl 2002, p180).

[9]See (Pruyt 2006b). Postpositivist practice would try to find out the probably objectively true model, critical pluralist practice would explore joint and separate models in order to learn, pragmatist practice would prefer a model that feels good and that advances towards the goal, constructivist practice would treat both views just as equally valuable or would try to construct a joint view/meaning.

- test the (different) behaviour(s) to reality and possibly re-adjust or falsify the underlying model structures and thus the assumptions held by these parties;
- integrate the different views –even on different levels– in holistic models and frame conflicting views in a broader perspective;
- get insight into which strategies and goals might be harmful and thus resisted and which might be acceptable to different parties and therefore supported;
- arouse commitment of multiple parties through insight into the common interests, advantages and gains.

But different or conflicting views are not easily taken into account in stand-alone system dynamics strategy evaluation and selection –except for the consensual approach which leads to a single group model and a single set of results. Again, the combination of system dynamics and multiple criteria decision analysis could help out. Two approaches are then to be distinguished:

- The consensual approach: all assumptions could be integrated in one system dynamics model and one multiple criteria decision analysis model with one or different preference sets. The simulation results and preference set(s) could then be used to find consensus strategies.
- The compromise approach: different system dynamics models could be developed for different parties with divergent/conflicting views leading to different system dynamics simulation outputs which are the inputs/evaluations of the multiple criteria decision analysis/analyses. These evaluations together with the different preference sets could be used in one or different multiple criteria decision analysis/analyses to gain understanding in the different perspectives and find the preferred and resisted strategies which could then lead to a set of compromise strategies that are for example not resisted by any of the parties.

Both approaches could be applied in non-participative, semi-participative and participative modes. And in both cases, ethics could be used to help decide who/what/which views/times scales matter and should be included and which ethical principles ought to be applied.

3.4 Uncertainty and Robustness

Dynamically complex multi-dimensional issues are mostly characterised by many types of uncertainties[10]. Uncertainty –especially inherent randomness of nature and human behaviour, and epistemological, methodological and technical uncertainties– is considered so important by most system dynamicists that it strongly influences the mainstream system dynamics methodology and the interpretation of the modelling results: mainstream system dynamics is concerned with 'behaviour modes, dominance of modes and dominance transfer, not with precise numerical values' (Coyle 1998, p356). Mainstream system dynamicists also have –apart from their specific attitude towards uncertainty and their specific interpretation of modelling results– several techniques and tools at their disposal to actively explore uncertainty: (i) behaviour mode, policy (and numerical) sensitivity analyses of the outputs and conclusions to different values, alternative structural formulations and choices of model boundary, (ii) formal scenario analysis, (iii) the exploration of different views, (iv) validation (only relevant for 'hard' system dynamics), (v) fuzzy logic, (vi) probability based methods, (vii) hedging oriented methods, and (viii) qualitative uncertainty discovering[11]. They also actively use soft variables and lookup tables to deal with uncertain but potentially important inputs and relations.

[10] Uncertainty is defined here 'as the entire set of beliefs or doubts that stems from our limited knowledge of the past and the present (esp. uncertainty due to lack of knowledge) and our inability to predict future events, outcomes and consequences (esp. uncertainty due to variability)' following (van Asselt 2000, p88) who deals extensively with uncertainty and risk in modelling.

[11] The phrase 'qualitative uncertainty discovering' is used here in the sense of qualitatively tracing out the possible structures and dynamics –which helps identify potential uncertainties and risks related to different structural representations, structural options, and leverage points (Mayo, Callaghan, and Dalton 2001, p269). The process of discovering risks and uncertainties could be greatly enhanced by qualitative system dynamics.

Because of the assumed overriding importance of uncertainty related to the real-world, limits of models and data, they put less emphasis on numerical uncertainty and the reduction of uncertainty, and focus instead on behaviour mode sensitivity, policy sensitivity and robustness (of models, policies and systems[12]). , on preparing decision-makers for uncertainties and risks through enhancing the understanding of the system behaviour and on building consensus and commitment (to the resulting decision) between the main stakeholders so as to reduce uncertainties regarding the actual implementation.

But uncertainty and robustness are only *indirectly* taken into account in the system dynamics strategy selection process, not directly as might be expected. They could be explicitly and directly taken into account in the strategy evaluation process if system dynamics is combined with multiple criteria decision analysis: system dynamics could then be used to explore uncertainty and robustness and multiple criteria decision analysis to take them formally into account in the strategy evaluation process. In practice, this could be done in several ways.

First, *sensitivity analyses* could be used, during the quantitative system dynamics phase, to assess the impacts of uncertain parameters, initial values, different structural formulations and broader boundaries, which results in outputs in the shape of intervals, distributions, fuzzy or qualitative evaluations (like 'very sensitive'). These can be dealt with in the subsequent multiple criteria decision analysis as (i) additional criteria to deal separately with uncertainty, or as (ii) interval, stochastic, fuzzy or qualitative evaluations –at least in multiple criteria decision analysis methods that are able to deal with these types of inputs– in the normal content criteria. The smaller the intervals are, or the less the results vary, the more robust the models and policy recommendations are. Hence, the additional criteria are of the minimising type. In case of evaluations of the interval, stochastic, fuzzy or qualitative type *within* the evaluations (without creating additional criteria), the treatment partly depends upon the particular multiple criteria decision analysis method chosen, but also upon choices depending on the issue, the decision-maker(s) and the particular criteria. In the case of interval evaluations, the choice could for example be made to take the full intervals, or only part of the intervals (like only the 80% confidence interval or the interval worse than the base case value), or still only the worst values into account.

Second, *formal scenario analysis and structure analysis* could be used, during the system dynamics phase, to obtain significantly different views and to represent different points of view which result in different sets of evaluations for the same –or even different– aspects/criteria. These can again be dealt with in the subsequent multiple criteria decision analysis by means of additional criteria to deal with different sets of evaluations with different inter-criteria information (structures) or –in the normal content criteria– using multiple criteria decision analysis methods that are able to deal with interval evaluations, fuzzy number evaluations or qualitative assessments instead of point evaluations. Again, the smaller the intervals are or the less the results vary in the case of additional criteria, the more robust the models and policy recommendations are.

Also during the system dynamics phase, *qualitative uncertainty discovering* by means of qualitative what-if explorations, qualitative assessment of uncertainties and potential risks and out-of-the-model-and-box speculation result in qualitative or fuzzy assessments of uncertainties and potential risks. These could again be taken into account in the subsequent multiple criteria decision analysis phase by means of additional criteria in methods that are able to deal with such evaluations.

In the multiple criteria decision analysis, different inter-criteria information (structures) could also be tested –by means of different weight sets, weight intervals, fuzzy weights, et cetera– to assess the influence of different preference or inter-criteria information structures. This could provide additional insight.

The *robustness of the policy recommendations*, can only be checked by taking into account the whole decision aiding multi-methodology –thus both the system dynamics *and* multiple criteria decision analysis phases which lead *together* to these policy recommendations. The question could then be asked as to what changes would be needed to modify the policy recommendations arrived at using the system dynamics and multiple criteria decision analysis models. The more change (or

[12]See i.a. (Richardson and Pugh III 1981), (Lane 2000, p17), (Groessler, Miller, and Winch 2004, p81)

uncertainty) required to switch policy recommendations, the higher the robustness of the policy recommendation. In the domain of multiple criteria decision analysis, the term robustness is also used in this sense and extensions of some methods exist to explore this robustness explicitly.

In the end, this allows to take uncertainty related to the data, models, scenarios and preferences into account in the combined system dynamics and multiple criteria decision analyses and to test the overall policy sensitivity. If the policy recommendations do not change much, or if the strategies/structures remain good, in spite of varying data, model formulations, scenarios and preferences, then the models and policy recommendations are robust.

3.5 Flexibility

Matching system dynamics and multiple criteria decision analysis allows to handle flexibility more effectively than stand-alone system dynamics: system dynamics could be used to explore and assess the flexibility of systems and strategies, which could then be integrated and evaluated using multiple criteria decision analysis. Two different types of uncertainty could be distinguished.

Short term or tactical flexibility allows the quick adaptation to short-term opportunities and threats. This kind of flexibility can be build into system dynamics models or could be estimated directly. If built-in, it will be apparent in simulations and sensitivity analyses. It will very probably lead to somewhat less efficient but more robust results: they will be more stable in case of external changes, and will thus narrow down the sensitivity intervals. This flexibility could then be integrated indirectly in the multiple criteria decision analysis by means of the smaller sensitivity intervals if built into system dynamics models, or directly by means of additional criteria to take the flexibility explicitly into account.

Long term or strategic flexibility is about keeping strategic long-term options open and is in that sense opposite to lock-ins. The options open are those that could still be reached –without too much difficulty– from the state of the system at a particular moment in time which means that there needs to be at least a dynamic path linking the current state to the optional state. It could be measured by the number of futures kept open or the efforts/resources needed to open-up other futures. Although simple in theory, its measurement is rather difficult in practice, as it is in system dynamics. Therefore, the subjective assessment of the number of *long term* options open or the ordinal evaluation of the flexibility of the different strategies at specific moments in time could be suggested for the assessment of this type of flexibility. Additional criteria could deal with these estimates in the multiple criteria decision analysis.

3.6 Sustainable Development and Ethics

Many DCMDS issues could also be seen as cases of sustainable development. Sustainable development is often defined as development which meets the needs of the present without compromising the ability of future generations to meet their own needs. As such, the term could be used in the sense of the integration of local *and* global, short-term *and* long-term, economic, environmental, social *and* cultural considerations. The combination of system dynamics, multiple criteria decision analysis and ethics then seems to be extremely interesting for dealing with sustainable development: this methodological combination allows to take into account these dimensions on these time scales from different point of view as well as other ethical arguments.

But how could it be made sure that all these important aspects, time scales and perspectives/parties are taken into account? Different approaches are to (i) depart from all important parties concerned and take the aspects they consider important at important moments in time into account, or (ii) depart from all important intrinsic dimensions and split them out into possibly important aspects at important moments in time. These aspects are also to be found in the system dynamics models developed from these different views. If this is not the case, then it needs to be considered whether the aspects are really important enough to be taken into account in the multiple criteria decision analysis, or whether the models need to be extended.

Still, this is –without a guiding (ethical) framework– more of an art than a science. Several system dynamicists have called for the explicitly consideration of moral consequences of strategies,

Table 1: The fictive perspective of the EU Commission

view EC	CO_2 f_{1EC}^{2010}	CO_2 f_{1EC}^{2020}	CO_2 f_{1EC}^{2050}	CO_2 f_{1EC}^{2100}	Price f_{2EC}^{2010}	Price f_{2EC}^{2020}	Price f_{2EC}^{2050}	Price f_{2EC}^{2100}	RES f_{3EC}^{2010}	RES f_{3EC}^{2020}	RES f_{3EC}^{2050}	RES f_{3EC}^{2100}
BC	-	- -	- -	- -	+	+	+	+	o	-	+	+
POL2	o	+	+	+	o	o	o	o	o	+	o	o
POL3	o	+ +	+ +	+ +	-	-	- -	- -	o	o	-	-

(- - stands for example for very bad, - for bad, o for neutral, + for good, and + + for very good)

Table 2: The fictive evaluations of the umbrella organisation of the electricity sector

view sector	Invest f_{1SECT}^{2010} [10^9€]	Invest f_{1SECT}^{2020} [10^9€]	Invest f_{1SECT}^{2050} [10^9€]	Invest f_{1SECT}^{2100} [10^9€]	Profit f_{2SECT}^{2010}	Profit f_{2SECT}^{2020}	Profit f_{2SECT}^{2050}	Profit f_{2SECT}^{2100}
BC	204	682	2810	7790	+	+	+	+
POL2	176	688	2550	5480	o	o	o	o
POL3	180	630	2270	4850	-	-	o	o

and hence for consequentialist ethics to be included system dynamics practice. Heffron (2004) also calls for the inclusion of deontological (Kantian) ethics. And other ethical theories or schools –such as feminist ethics or virtue ethics– might also be considered for inclusion. Ethical perspectives and frameworks could then be integrated explicitly in the combination of system dynamics and multiple criteria decision analysis –by means of (deontological, consequentialistic and other) ethical filters, ethical preference sets, and so on– or be used in the process to guide questions about what matters. The explicit consideration of ethics might also be used to model, simulate, and evaluate what *ought* to be done in case of dynamically complex multi-dimensional issues.

3.7 System Dynamics, Multiple Criteria Decision Analysis and Ethics Applied to the Example

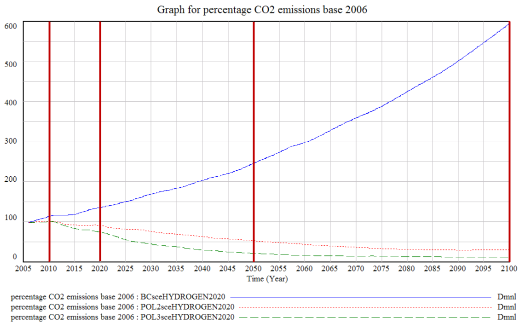
In this subsection, all of the above is applied step by step –just to illustrate the idea– to the example discussed in subsection 2.3. The multiple criteria decision analysis method used here is also a very simple –even simplistic– and non-technical elimination method which nevertheless allows the integration of multiple dimensions, multiple time scales, multiple views, and other aspects such as robustness and flexibility.

Suppose that the perspective of the EU commission is modelled and simulated with the aforementioned system dynamics model. And suppose that the commission judges the following three aspects to be sufficiently important to be taken into account: the total annual CO_2 emissions (see figure 6a), the fraction of renewable generation of total electricity generation (see figure 6b) and the electricity prices to consumers (see figure 6c).

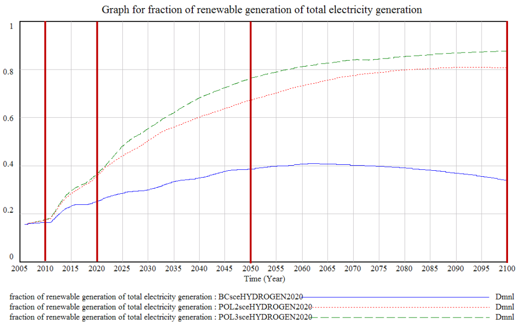
And representative relative time scales judged sufficiently important for this issue are for example the year 2010 (the short term), the year 2020 (the medium long term), the year 2050 (the long term) and the year 2100 (the very long term). These discrete milestones in time are shown in the figures. Suppose that the simulation results –which are quantitative in form but qualitative in interpretation– are interpreted in an qualitative/ordinal sense. The resulting qualitative evaluations on these time-scale-aspect couples are displayed in table 1. The evaluations of the BC strategy and the POL3 strategy are (very) good on some criteria, but (very) bad on other criteria, whereas the more moderate POL2 strategy is mostly neutral or positive on all criteria.

Suppose also that the commission wants to take into account the major concerns of the umbrella organisation of the electricity sector and of two 'well-oiled' lobbying machines of potentially important technologies, the wind power lobby and the clean coal lobby. For the multiple criteria decision analysis, it does not matter whether the evaluations of the different views have been as-

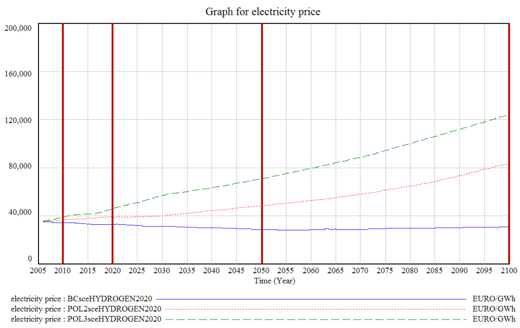
Figure 6: Some important aspects and relevant time scales



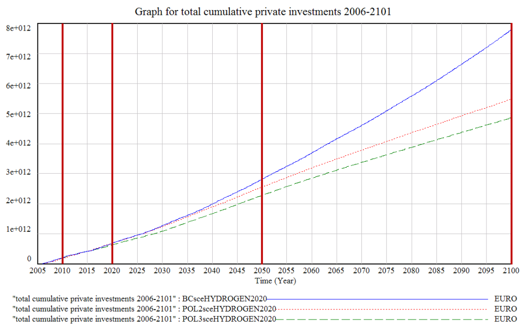
(a) CO_2 emissions and relevant time scales according to the EC perspective



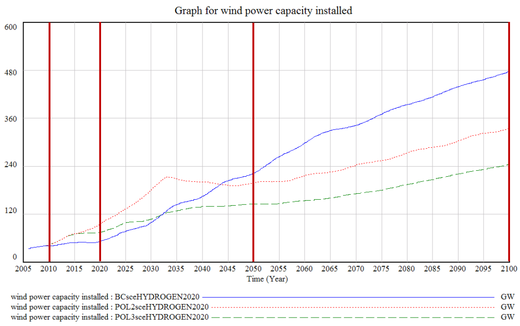
(b) fraction of renewable generation of total electricity generation and relevant time scales according to the EC perspective



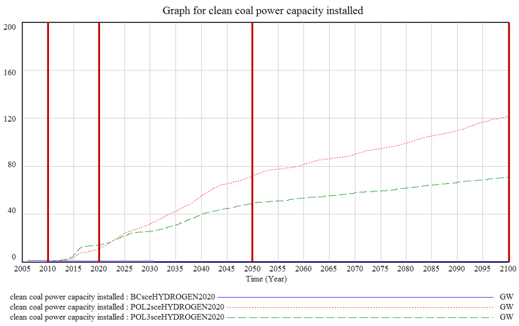
(c) (consumer) electricity prices and relevant time scales according to the EC perspective



(d) total cumulative private investments from 2006 on and relevant time scales according to the perspective of the umbrella organisation



(e) wind power capacity installed and relevant time scales according to the wind power lobby



(f) clean coal power capacity installed and relevant time scales according to the clean coal power lobby

Table 3: The fictive evaluations of the wind power lobby and the clean coal lobby

view WIND	WP inst f^{2010}_{1WIND}	WP inst f^{2020}_{1WIND}	WP inst f^{2050}_{1WIND}	WP inst f^{2100}_{1WIND}	view Clean Coal	CC inst f^{2010}_{1d}	CC inst f^{2020}_{1d}	CC inst f^{2050}_{1d}	CC inst f^{2100}_{1d}
BC	40	52	222	477	BC	1	1	0	0
POL2	43	94	198	335	POL2	1	11	72	122
POL3	43	75	144	244	POL3	1	14	49	71

Table 4: Assessment of robustness and strategic flexibility

view$_2$	Robust f_{1b}^{2010}	Robust f_{1b}^{2020}	Robust f_{1b}^{2050}	Robust f_{1b}^{2100}	Flex f_{2b}^{2010}	Flex f_{2b}^{2020}	Flex f_{2b}^{2050}	Flex f_{2b}^{2100}
BC	-	-	-	-	o	o	-	-
POL2	-	+	+	+	o	+	+	+
POL3	-	-	-	-	o	o	o	o

sessed with the same approaches, (system dynamics) models, data sets, et cetera, or not. Now, the two major concerns of the umbrella organisation of the electricity sector are the total cumulative amount of private investments needed in the EU25 electricity system from the year 2006 on (see figure 6d), as well as the expected profitability of the sector (see table 2). The major concern of the wind power lobby is the wind power capacity installed (see figure 6e and table 3), and the major concern of the clean coal lobby is the clean coal power capacity installed (see figure 6f and table 3). Finally, the commission also wants to take some measures of uncertainty/robustness and strategic flexibility into account, in this case by means of additional ordinal criteria (see table 4).

It should be clear that there is no unambiguous best strategy, and that any strategy selection method used for this problem requires some form of additional information. The additional information required by the elimination method consists of the minimally acceptable states (or thresholds) for each of the criteria. All strategies with evaluations worse than these minimal acceptable states are eliminated. This could be seen as a consequentialist ethics filter since strategies are eliminated that are unacceptable for parties concerned on important criteria.

Suppose that all strategies should at least be neutral on the criteria specified by the commission, then the BC and POL3 strategies are eliminated. And if –according to the umbrella organisation– total cumulative investments by the year 2050 need to be less than €2500 billion and if the profitability should be at least neutral, then no strategy survives the elimination from the point of view of this umbrella organisation. The combination of the system dynamics and multiple criteria decision analysis models could then be used to understand why this is the case and marginal changes could be proposed to remedy the problem. A 'marginal' increase of the limit on the total cumulative investments by the year 2050 with about €50 billion –or investment subsidies of that amount– would turn POL2 into an acceptable one.

The wind power industry might reject the BC for its bad short and medium term scores and POL3 for its bad (very) long term scores. Whereas the BC would most certainly not be acceptable to the clean coal lobby.

So, the POL2 satisfies all content criteria. Now it could be checked whether this strategy is sufficiently flexible and robust (o or +). Table 4 shows that this is indeed the case, except for f_{1b}^{2010} which is negative for all strategies considered.

In the example, the small amount of strategies was immediately reduced to a single acceptable strategy (or none at all). In real cases, much more strategies need to be evaluated simultaneously. By applying these elimination/ethical filters, the set of strategies considered could then be reduced to a set of acceptable strategies on all dimensions, aspects and time scales and for all views considered. Then a strategy could be chosen from this set, knowing that it is at least acceptable to all on all important dimensions and time scales. But what if no strategy survives the elimination? Then none of the strategies considered is appropriate and other strategies might be looked for, or the thresholds might be relaxed, or the methods might be used to try to understand why this is the case.

Here, the multi-methodology has been used to look for compromise solutions, but it might equally well be used to build consensus, to increase understanding, or to support negotiation processes.

4 Conclusions

It could be concluded in general that:

- decision-making in case of dynamically complex multi-dimensional societal issues is extremely complex, among else because of the multiple dimensions, multiple time scales, multiple parties, multiple views, many uncertainties, power relations, and so on;
- system dynamics is useful for decision-making in case of dynamically complex multi-dimensional societal issues, but not is not sufficient in stand-alone mode;
- the consistent matching of system dynamics approaches, multiple criteria decision analysis methods and ethics might be very appropriate to deal with DCMDS issues and sustainable development;
- relative time scales could be used to match continuous system dynamics and discontinuous multiple criteria decision analysis evaluation techniques such that the evaluations on the aspects as well as the additional qualitative information that it contains could both be taken into account in strategic decision-making, which results in different additional pseudo-independent criteria per aspect dealing with the multi-dimensional goals, the paths, possible resistance, et cetera, of the different aspects;
- uncertainty, robustness, resilience and flexibility are important for dealing with dynamically complex multi-dimensional issues and could be integrated in the multi-methodology, but to different degrees and in different forms depending on the issues and especially on the methodological basic assumptions;
- multiple parties, views and preferences are also important for dealing with dynamically complex multi-dimensional societal issues and also depend on the issues, parties and paradigmatic basic assumptions, but different approaches remain possible from non-participatory over semi-participatory to fully participatory and from integrating all views and preferences to keeping them apart;
- dimensions and aspects could be adequately captured in the multiple criteria decision analysis part of the multi-methodology by multiple criteria at different relative moments in time, and criteria dealing with important characteristics such as uncertainty, robustness, resilience, flexibility, et cetera, could be added;
- the multi-methodology matching system dynamics, multiple criteria decision analysis and ethics could be adapted to look for strategies to improve structure and time evolutionary behaviour which are good (appropriate and acceptable on different dimensions on different time scales), ethical (respecting the other on different time scales), robust, resilient and flexible.

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