International Congress on Environmental Modelling and Software

6th International Congress on Environmental Modelling and Software - Leipzig, Germany - July 2012

Jul 1st, 12:00 AM

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International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Coupling the ExtendSim platform with HEC-HMS for modeling irrigation strategies

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Abstract: the quantitative water management of the Charente River in France is a major policy concern because of freshwater scarcity in summer. In the context of SPICOSA project (Science and Policy Integration for Coastal System Assessment),) this policy issue was chosen to apply the System Approach Framework (SAF) methodology. This led to modeling irrigation management strategies to quantify its impacts on various uses. It was decided to model all sub-systems within the ExtendSim® platform as a first attempt for model-integration. For this purpose a hydrological model has been entirely programmed in ExtendSim ModL language. This allowed us to understand and quantify some interactions among the different components of the socio-ecosystem but it also revealed the limits of an “in-line” ad-hoc hydrological model. In order to lessen uncertainties and to enhance the capabilities of the model, a new version of the model has been developed with a different strategy. In a second round of development, an external hydrological model has been built in HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System) and interfaced with ExtendSim to work as a source of forcing. This strategy has proved to be much more efficient to model water shortages without renouncing the benefits of system-modeling inside ExtendSim platform and with the advantage of a powerful software dedicated to hydrological modeling. Using this experiment, the paper discusses the case of “in-line”, “on-line” or “off-line” coupling modes to serve the objectives of policy orientated complex socio-ecosystems modeling. This research has been funded under the “Global Change and Ecosystem” priority of the 6th RTD Framework Program of the European Union.

Keywords: System Approach Framework; SPICOSA; ICZM; system modelling; model coupling; hydrology; irrigation.

1. SPICOSA EXPERIMENT

SPICOSA (Science and Policy Integration for Coastal System Assessment, 2007-2011) is an integrated project funded under the 6th Research Framework Programme of the European Union in support of European agenda for Integrated Coastal Zone Management (ICZM). The project applied system thinking to incorporate the ecological, social and economic dimensions (ESE) of coastal social and ecological systems, in order to support policy design for complex environmental issues. The result is a problem orientated methodology, called the System Approach Framework (SAF) that aims at integrating multidisciplinary scientific expertize and knowledge held by stakeholders. It encompasses a participatory process to organize the knowledge around a policy issue and a simulation model in the ExtendSim® platform was developed to explore management scenarios. In SPICOSA, the SAF procedure was defined in five steps: policy issue mapping (including identification of knowledge sources), design step (soft system or conceptual modelling), model formulation, appraisal and output (interpretive narrative of scenarios) (Tett et al. 2011). SPICOSA has tested the SAF in 18 coastal study site applications (Hopkins et al., 2011; www.spicosa.eu).

Along the French Atlantic coast, the Charente river watershed and associated coastal waters was one of the SPICOSA case-study in Europe (Pertuis Charentais Study Site Application). Coastal waters are strongly impacted by the Charente River and two major primary industries in the area depend on freshwater availability: agriculture, dominated by maize production, and shellfish farming. Due to upstream demand the river suffers from low flow in summer, putting tension on the policy priority which is to secure the supply of drinking water to households in the coastal zone where the summer population is very high because of tourism. It also makes it difficult to attain the good ecological conditions for the river and coastal marshes required under the EU Water Framework Directive and its national transposition, the French Water Act. Therefore, the quantitative management of water in the watershed and its impact on the coastal waters has been chosen as a policy issue for participatory building of a system model that allows integrated assessment and policy scenario development along the SAF methodology lines (www.spicosa.eu/pertuis_charentais).

The Charente river system has been modelled with the software ExtendSim® (www.extendsim.com). A readable projection of the ESE components was drawn in a Resource-Uses-Governance (RUG) structure (Figure 1). A series of nested models describes each sub-system starting with a low resolution and are then developed up to the most level of complexity agreed upon by the local SAF team formed by a small group of researchers, managers and stakeholders (Mongruel et al. 2011).

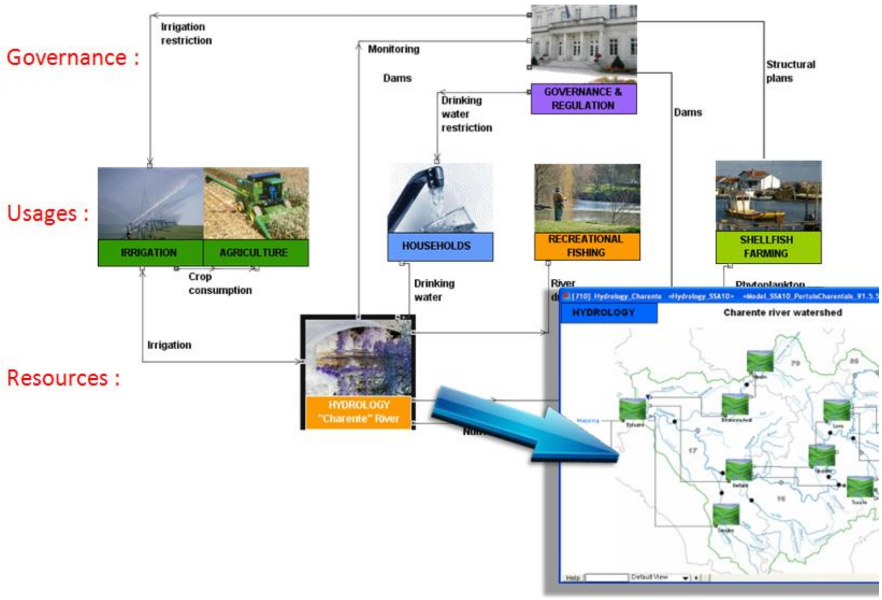

Figure 1. The Pertuis Charentais ExtendSim model and details of hydrology sub-system

A major issue for such system modelling is to decide if a sub-system should be modelled in-line, on-line or off-line. We call the subsystem "in-line" when it is calculated inside the simulation platform. An "on-line" sub-system computes in another program or library outside the platform but remains synchronized in order to communicate both ways with the platform. An "off-line" sub-system does not depend on the platform results and can be computed separately as long as the platform has access to its outputs as forcing data. The absence of "on-line" feedback may be justified for technical reasons or because the process works simply as an external forcing. In the case of ExtendSim, the choice of modelling sub-systems in-line, on-line or off-line may depend on the availability of resources needed to develop new programs in ExtendSim ModL language. Despites the recognized potential of ExtendSim for simulation modelling, one weakness lies in that ModL does not offer the capabilities of modern languages for scientific computing (for example: no objects, no complex data structures, lack of shared variables, no easy file access and database records only accessible by a numeric index).

2 THE CASE OF HYDROLOGY IN MODELLING CHARENTE RIVER MANAGEMENT

The hydrology sub-system was initially entirely written in ExtendSim language based on an existing reservoir model, the CycleauPE described by Bacher et al. [2010]. This lumped model gives a representation of elementary watersheds by surface flow, catchments and ground reservoirs. It fits well with the idea of system modelling and gives a satisfactory representation of the hydrology of the 10,549 km² of Charente watershed (Figure 1). The reason for developing a completely new hydrological code in ExtendSim was that during the Design step of the model, it appeared that two factors may have a feed-back on hydrology. On one hand, the Irrigation sub-system may modify the river flow by its takings from the Charente River. On the other hand, the Agriculture sub-system is consuming the surface freshwater in summer. So, at first sight, the hydrology sub-system can't be off-line and needs to be computed in-line or, at least, as an on-line external library. The choice has been that an in-line programming would offer more advantage than interfacing with an external code for on-line simulations. This design raised many issues: mastering the original code, translating it into ModL with specificities of the system platform, debugging the code and the model which remained fragile for not having been tested on other cases. Nevertheless, during this first cycle of the SAF application, the resulting code allowed to build an integrated representation of the system suitable to simulate irrigation management scenarios and to measure the relevant impacts on uses and ecosystems.

But in the appraisal step, the hydrological component of the model, originally built for operational management of freshwater intake during dry periods, turned out to be an obstacle for good quality simulation. It led to many uncertainties, making it not suitable for long-term simulations that were needed to test alternative agricultural practices and reservoirs management strategies. Exploring the reason for that, it was discovered that the original model, successfully used by managers for weekly prediction during dry seasons, was in fact weekly reset by assimilation of observation data. This was taking the model away from the purpose for which it was intended, i.e. long-term simulation for management scenario testing, and opened the discussion for considering another modelling strategy for hydrological processes opening a new cycle in the development of the project.

3. RECONSIDERING THE "IN-LINE" CHOICE IN CHARENTE HYDROLOGY MODELLING

The choice of an in-line hydrology was based on a misunderstanding of some hydrological processes. It was not true to say that irrigation from rivers modify hydrology. It only concerns the river flows which are the consequences of runoff and, in the absence of groundwater recharge from rivers (karst), irrigation does not influence watershed hydrology. Furthermore, it was not true to say that the Agriculture subsystem has an impact on the hydrology. The surface losses calculated by hydrological models already take into account the evapotranspiration processes related to soil cover and crop production (see De Wit [1958]). By reconsidering the relationship between these subsystems and faced with the limitations of the first attempt, it has been decided to develop an off-line hydrological component based on a more powerful core, but consistent with system thinking that calls for coarse modelling but relevant in terms of capturing key interactions involved in problem assessment and design of policy options. A similar strategy was used by other study site applications in SPICOSA such as for the calculation of Nitrogen transport in the Scheldt case (www.spicosa.eu/scheldt_delta) where PC-Raster program (www.PCRaster.nl) is continuously launched in batch execution for a single time step with varying parameters on input (land use).

The Hydrologic Modelling System (HEC-HMS) has been chosen to model the hydrology of Charente River. HEC-HMS is a completely integrated work environment designed to simulate the precipitation-runoff processes of dendritic watersheds (www.hec.usace.army.mil/software/hec-hms/). Compared to a distributed 2D model (such as PC-Raster), HEC-HMS watershed has the advantage in that we can use the same geographical projection as used to design Agricultural and Irrigation sub-systems. This allows for the same measurement and comparison points. Furthermore, facilities for modelling hydraulics components (pumps and reservoirs) which are part of the options considered for water management, is greatly appreciated in HMS. HMS can only run in batch mode without ability to dynamically change the parameters under control of another program during the execution. So, it can only be off-line.

4. INTERFACING HMS WITH EXTENDSIM

We wrote the program iHMSControl in Pascal-Delphi. This program is able to communicate with ExtendSim to read/write in the database files created by HEC-HMS. It can launch executions of HMS code in batch mode and can use the HEC libraries (DLL) to read the content of the database. Communications with ExtendSim are made via the IPC (Inter Process Communications) facilities offered by the old windows DDE (Dynamic Data Exchange) protocol mainly used because of its simplicity and efficiency. For the greatest speed of execution, the iHMSController uses an internal buffer for only sparse access to the database (Figure 2).

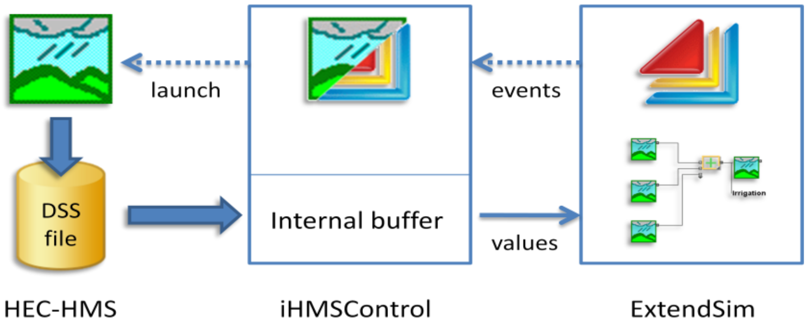

Figure 2. HEC-HMS and ExtendSim interface with iHMScontroler to access to the DSS database and provide hydrological forcing values and to launch new run of HMS in batch mode with modified parameters

Since 1967, the HEC programs series uses the facilities of a Data Storage System (DSS) for storing and retrieving scientific data in database. A DSS file contains all time series data, spatial-oriented gridded data or other data needed and calculated by a HEC program. Data are organized around an internal "path" representation including information such as the name of the object, the parameter calculated, the name of the run and other informations, eg: `//LUXE/ET-SURFACE/01JAN2000-01JAN2009/1DAY/RUN:SMA20002009/`. This descriptor is what we use in ExtendSim to access the values of the HMS simulation in DSS file via the iHMSController.

ExtendSim is an event-based scheduler. Each component receives elementary events during the run of the model (table 1). This event-oriented method is a key of the success integrating external programs into ExtendSim simulations. For each event, we program ExtendSim to send an "execute macro" whose data are the passed arguments. In addition, the iHMSController can modify the parameters of a run (eg. soil cover, values of ETP,...) and launch a new run of HMS in batch mode. This allows for scenario testing and for statistical testing of management strategies on similar series of climatic conditions.

Simulation event	Input	Output / comment
OnInit	*DSSpath*	*idx : index of buffered data serie*
OnSimulate	*idx, CurrentTime*	*Serie Data value at CurrentTime*
onEndSim	*idx*	*Free idx buffer*

Table 1. iHMSControl inter-processes exchanges based on ExtendSim events

In our case, each of the twelve ExtendSim components describing the Charente watershed is made of several blocks for accessing the relevant values in the DSS file (Figure 3). Thanks to DSS files, we can find all hydrological necessary values calculated for each watershed (river flow and other reservoir parameters). The Agricultural system uses the same principle for evapotranspiration values access.

5. THE NEW OFF-LINE MODEL OF CHARENTE WATERSHED

The new off-line model is based on a simple SMA (Soil Moisture Accounting) HMS model of Charente watersheds and its dual implementation on ExtendSim (Fig. 3).

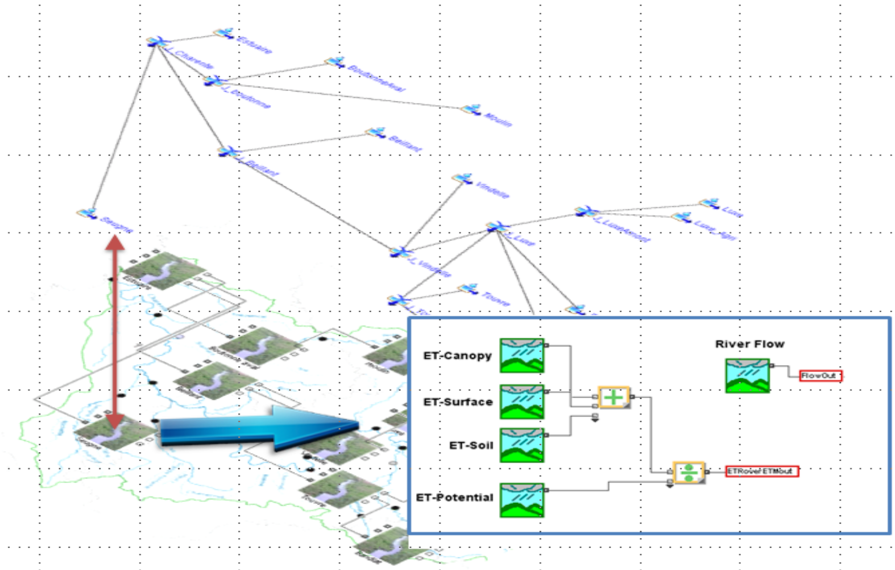

Figure 3. The hydrological system in HMS as a dendritic projection (top) and its dual representation in ExtendSim (bottom), each watershed is described with many components accessing HMS DSS files

The SMA model (see Bennett [1998]) is a reservoir model (canopy, soil to groundwater reservoirs) suitable for conservative long term simulations as long as we can give values of capacity and permeability of the different reservoirs. These are easily calibrated from literature references and observations. With HMS, a model can be created in a few days that allows for accounting of human actions such as taking water for irrigation in dry periods and for reservoirs recharge before winter time (Figure 4). For each watershed there are two components calculating surface losses: one for irrigated cultivated area and another for the other areas (forests, urban areas...). So, long term scenarios for land cover and/or agricultural practices become easier to simulate because the iHMSController can change the relevant values of HMS components and launch the program for a new hydrology computing cycle.

Irrigation takings are calculated in ExtendSim and subtracted from the river flow calculated in HMS. One can admit that the hydrograph routing is a linear process so, to be exact, the flow of irrigation must be routed in the same manner as all hydrograph are routed in HMS. This can be done because systemic representation of the components in ExtendSim uses the same dendritic representation as in HMS. The relevant component in ExtendSim only calculates the sum of the upstream irrigation-flow and applies a TLag value corresponding to the TLag of the relevant river. We suppose here that this extraction does not have influence on the hydrological process which is only partially true. Indeed there are some karstic groundwater charged by river flow and which are directly impacted by taking of water from the river. The groundwater reservoir values calculated in HMS and stored in DSS file make it easy to take account of these reservoirs on ExtendSim side and to simulate the underground in-takes. Figure 4 plots the output of the HMS model calibrated for wet periods, which is the theoretical flow of the river in absence of irrigation (blue line) and the observed flow of the river at the outlet of one of the sub-watersheds using 2001-2006 data. The graph provides an estimate of the impact of water taking by irrigation during the crop period at the geographical scale considered as relevant for policy discussion. Changing the scale of management unit in HMS and its dual representation in ExtendSim doesn't involve a large amount of time, contributing to the adaptiveness and flexibility required by the SAF methodology.

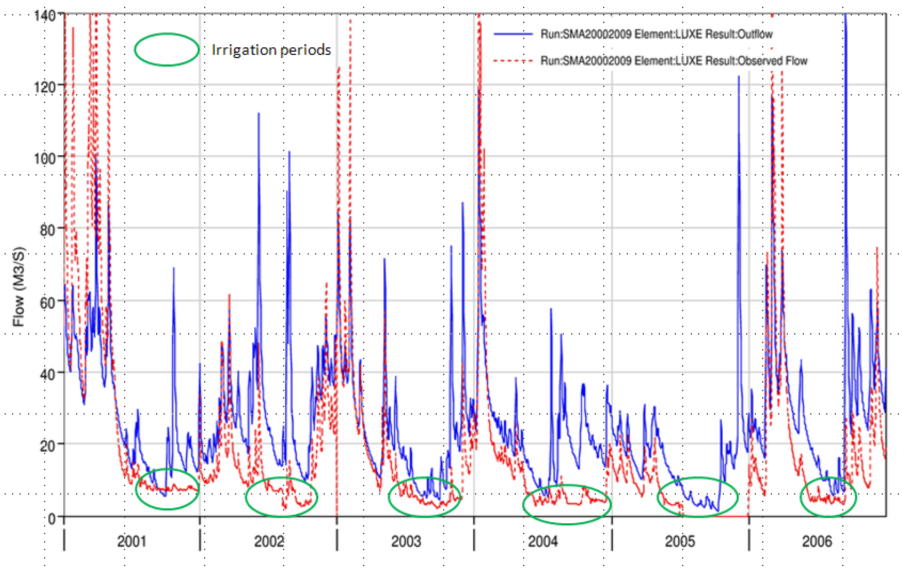

Figure 4. HMS model calibrated for wet periods showing the impact of summer irrigation on the river flow (in red : measurements, in blue: the HMS model without irrigation which is calculated in ExtendSim)

The feedback to agriculture uses evapotranspiration results in the Agricultural sub-system in ExtendSim® to calculate the loss of crop yield due to water shortage. For this purpose, Stewart & al (1977) formulation is used :

$$\frac{Y}{Y_M} = 1 - K_y\left(1 - \frac{ET_R}{ET_M}\right)$$

Ky is the hydric stress response coefficient related to the crop type. The daily evapotranspiration (ET_R) is calculated in HMS according to FAO formulation (1979) and the maximum evapotranspiration ET_M is given by monthly averaged tables.

The new model was developed and tested in few weeks, which is very short compared to the months required for the first hydrological model. Once the calibrations are made, it will be ready for simulating scenario of irrigation management as well as promising developments for reservoir management strategies. The choice of HMS allowed for a much more efficient integration of the hydrology of the river in the simulation model.

6. DISCUSSION: THE SAF BEYOND SPICOSA

Testing the effectiveness of an alternative strategy in system modelling to support water management policy design in Charente is part of SAF methodology development beyond SPICOSA experiment. This approach differs significantly from that which was at work initially, i.e. a strong Design leading to the in-line integration of a hydrological component rather than to the integration of the hydrological science. In the Charente case, hydrological expertise in the SAF team considered a model that had been successful to support the daily work of managers and modellers insisted on having it re-coded in the simulation platform. The role of hydrology in the feedbacks of the system was also over-estimated. That resulted in poor performance of the hydrological component for simulation of long term outcomes or alternative management choices required for policy discussion. As we have shown here, coupling irrigation, crops and hydrological processes do not necessarily call for an in-line model that requires long developments and restricts future development of the project.

This weakness is an illustration of the risk of a drift between end-user expectations and performance of the simulation tool in a "modeller driven" modelling work. By drift, we mean the increasing gap between end-user needs and science delivering despite the initial intention to build operational models in a participatory way (Lample et al 2011). Similar drift is observed, though for different motives, in the case of "actors-driven" approaches which tend to lead to "solution selling" rather than "problem exploration". In policy oriented participatory modelling, actors can be modellers, representatives of interest groups, managers, decision-makers or any other kind of "expert". The modellers generally insist on creating new code. Decision-makers are well known to be seeking for "a solution" whatever it is. And this "solution" often builds as a social belief leaving little room for genuine exploration of alternative futures and learning processes. This is exactly what happened to the project during the Design step where the modellers and managers solutions were adopted without sufficient review of knowledge and questioning about policy making relevance.

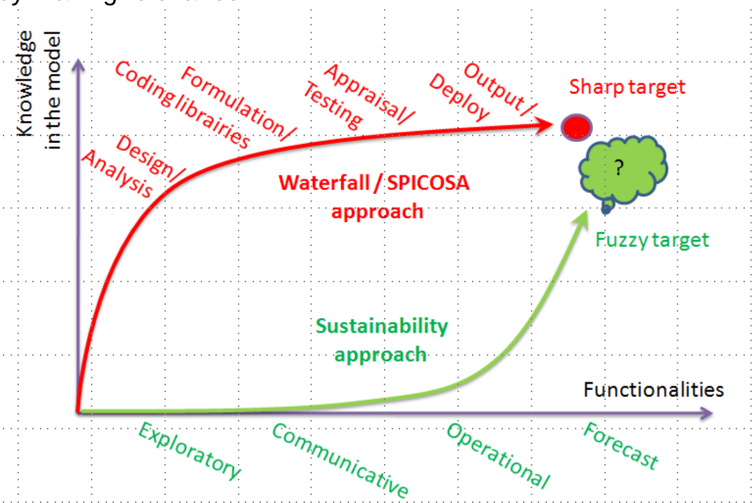

Figure 5. The waterfall approach leading to "ballistic trajectory" (top) versus the sustainability approach for co-constructed ESE models (bottom).

In response to this difficulty encountered in SPICOSA experiment and in many other similar projects (Fulton, 2011), it is important to promote an "objective driven" rather than an "actor driven" approach. In the case of addressing complex environmental problems, a sustainability-driven approach would first aim at managing the uncertainties under a model development agenda based on continuous knowledge acquisition rather than on a ballistic trajectory of steps imposed by a too strong design phase (Figure 5 below). Complexity in environmental policy relates first to the fact that different interests are concerned, so social choice is a matter of arbitrage resulting from a negotiation process, including power relation, rather than a pre-defined normative rule. Secondly, complexity is in the level of uncertainty within our knowledge of interacting social and natural processes at play in the policy issue. Having that in mind, participatory modelling should be an open process towards the goal which is generally a very "fuzzy target" when exploring policy options. This is prerequisite for a better handling of knowledge and interest claims.

The SAF as tested in SPICOSA, based on a strong Design, appears to be similar to classic steps used for model building and inherited from the Waterfall method of Benington (1983). A sustainability driven approach is very different from the waterfall approach (figure 5) which begins with a strong design assuming a sharp and well defined target. Such Design dependence has serious consequences when the target is fuzzy as any change in trajectory rapidly becomes unaffordable. Under the sustainability approach, the models and the engagement process grow in quality only at the end of trajectory precisely when the target becomes sharper due to reduction of uncertainties. As a lesson learned from SPICOSA experiment, we have suggested (Lample et al, 2011) an agenda based on four stages corresponding to the stages of knowledge acquisition: Exploratory, Communicative, Operational and Forecast with a Design-Formulation-Output-Appraisal loop to maintain the interaction among participants that works as a quality insurance loop.

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