Playing with flows in transition territories

Introduction

These environmental and social challenges of the Anthropocene require us to imagine and implement alternatives to the current global economic organization. Accounting in biophysical flows (material, energy, land use, …) is one grid of analysis providing insights on the alternatives' sustainability (strong sustainability and ecological economics frameworks) [6, 8, 12]. These tools are indeed relevant to highlight systemic effects (interdisciplinary understandings, spatial and temporal scales) on resources and important pressures to consider for the transformation of territories. If this biophysical flow vision may be very useful, it however remains for expert use only. However, one of the challenges of transition territories is to involve the populations in participatory processes in order to put their knowledge, wishes and specific capacities for action in synergy [1, 2, 10, 30]. Among the several participatory tools, serious games have long since proven their ability to sensitize to sustainability issues, facilitate learning and support changes. This paper presents an exploratory work to get insights on how playing with material and energy flows, fostering biophysical accounting and systemic vision learning to support stakeholders in territories' transitions. We first discuss general needs to support stakeholders in transition territories. We then detail how biophysical flows can be a tool to improve territories' sustainability. Section 3 and 4 are related to literature and some exploratory field experiments about flows involvement into games. We finally discuss the results in Section 5.

1 Supporting stakeholders in transition territories

Transition of territories (cities and / or rural area) requires multiple forms of engagement and adaptation from their stakeholders [21, 23, 26], under several biophysical and socio-institutional constraints. In this research, we focus on two groups: in the first one, policy makers, public engineers and public administrators, in the second one, citizens, private operators, and representatives of the civil society. The first have to cope with policy design, implementation and adaptation, while the second may consider engaging in behavioral change at household, daily activities or business level. They also try to use their democratic power upon representatives to take action. New dialogue processes may be required for both. Transiting toward alternative socio-technical organizations is their common challenge, if they endorse it. It requires coordination and compliance with various constraints in terms of resource availability and use patterns, balanced satisfaction of stakeholders' expectations, and social or institutional norms. The related problematic framework shared with them can be formulated as: "how can we restructure our activities to cope now and later

with the bounded or declining resources (natural or socio-technical), considering the diversity of our needs and uses, the prevalent power structure and the current social and institutional situation?"; and to feed the methodological design: "what are the induced stakeholders' needs in terms of learning, adapting social norms, social relationships and practices?" Our assumption and analysis are based on a synthesis of the past research around the Wat-A-Game modeling toolkit and more than 180 offspring games [1, 10], and of applied research on material flow analysis (MFA) [8, 18] with a focus on biophysical consistency built on expertise and data reconciliation. In this paper, we target the following stakeholders' needs:

- Discovering and endorsing the systemic dependencies between multiple resources and activities in their living territories,
- Considering and assessing possible technical and social alternatives, by testing and discussing mutually their social and ecological impacts,
- Reflecting on social beliefs and preferences, and their consequences,
- Engaging all stakeholders in an informed deliberation and decision process, leading to actual commitments and actions.

When dealing with material flow for transition support, this requires to get the users to access and explore not only the material flow dynamic under impact of adaptation actions, but also to engage in social procedures opening toward new social norms and practices.

2   Biophysical flows as a tool to evaluate sustainability

Among the diverse tools developed to support transitions, we focus here on models centered on biophysical accounting. These tools aim at representing the society's functioning, analyzed through the biophysical (material and energy) flows controlled by humans, and highlight human-nature interactions and evolution over time [9, 12]. Among various environmental assessment methods (life cycle analysis, input-output analysis, footprints, ...), we focus here on material and energy flow analysis (MFA), tracking extraction, production, transformation, trade and waste flows [6, 8, 9]. MFAs provide insights for resource management and related pressures in territories and, providing adapted data gathering methods, can be worked on at company, local, regional and national scales [3, 12].

These tools ease systemic thinking. Because they are based on biophysical coherence (thermodynamics laws dealing on mass and energy), they track all flows thus reducing blind spots [9] : the relations between sectors are highlighted, as well as indirect links and thus indirect pressures. Some systemic effects are especially pointed out, such as competition for the use of resources (many use require the same resource), geographical pressure transfer (a territory externalizes pressures when local consumption involves external production inducing pressures in the producing territory), transfer between pressures (a production alternative shifts the pressure on the environment from one type to another), …. [4]. Such clarification also reveals linkages between resources, organization and pressures. Moreover, these tools help to

discuss the social system behind and the power and dependencies between stakeholders and the resource dynamic.

As they provide evidence for resource management, these tools are already used to support decisions. Companies and supply-chains use them to optimize material flows and waste streams in the production process (industrial ecology). Regions use them as a diagnosis tool to set up monitoring programs aimed at designing suitable strategies (e.g., regional bioeconomy strategies, regional biomass plan…). It is also an evaluation tool, used to assess the impact of scenarios of socio-economic development on resources and identify the resulting pressures [3, 8]. A more extensive review list can be found in [12].

Yet, these models are limited. Based on quantitative description, they require data and expertise, implying consequent gathering costs (data is not always available at the scale at which the decisions can be made, especially for local problems) [3, 9], and methodology-dependency for knowledge collection. They are static (describing the current state of a system). There is no information collected and shown on derivatives and controls.   Hence they cannot support dynamic simulation or show flows' evolution over time. Moreover, if the biophysical focus is relevant to detach from market considerations and focus on material and energy flows, it does not provide any decision framework that could help users to go beyond description and couple their social considerations to the biophysical constraints. Meanwhile social control is not represented either. To support decision coping with social constraints, these biophysical models should be coupled with social models (endogenous social integration) or be included explicitly in collective decision processes through participatory modeling [30] or simulation like role-playing games (procedural social integration).

The latter approach, activates transdisciplinarity[1] in a post-normal perspective, and involves non-scientific stakeholders who, by their social interaction and access to biophysical models, recouple both domains. In literature [12], this is mostly done in a « trickle-down » (from researchers towards leaders), « transfer to translate » (scientists pay an effort to transfer knowledge to managers who translate it into action) or « users-push » (users -mainly leaders- ask researchers about the knowledge they require) ways. Yet, there still exists a gap regarding the involvement of a larger scope of stakeholders into the use of these models, especially in participatory processes with co-construction of the territory's transformations [14]. Such an involvement could be an opportunity to better understand the use and impact of MFA models into public decisions : do they really facilitate systemic thinking? Are they a good boundary object, fostering debate and deliberation (see [19] for example)? What could be a good decision framework to be coupled with these tools ?

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[1] We choose to consider transdisciplinarity as the collaboration between researchers from multiple disciplines with actors from non-scientific spheres [17].

3 How are flows dealt with in games in literature?

Games have long since proven their ability to foster territorial transformations. Here we wish to assess the MFA use and impact on stakeholders and this might hint towards new ways to include it into participatory simulation games. In this section, we explore some games involving flows and biophysical coherence (we do not claim any exhaustivity in the game literature, but only a preliminary exploration that seemed relevant for further interrogations). Based on the readings and on Section 2, we then introduce a framework to analyze them.

To constitute this literature, the following key-words have been used together with "serious game"and then filtered depending on how we evaluated their interest for the study. These key-words correspond to sustainability fields involving MFA : " material flow analysis", "territorial metabolism", "territorial ecology", "urban metabolism", "territorial metabolism", "social metabolism" and "socio-economic metabolism". We have chosen to present here only the games that seemed to involve biophysical flows or had an intention to sensitize to a systemic analysis of the biophysical structure. To this first category, some nexus games and games related to circular economy or industrial symbiosis have been added to the study, as well as a few resource management games involving biophysical flows without focusing on them [11, 13, 15, 16, 20, 22, 24, 25, 27]. A large part of this research being also inspired by the Wat-A-Game toolkit [1,10], which is a versatile modeling and game toolkit for water and other resource dynamic, we have included it for comparison sake. This literature is not exhaustive and is only aimed towards future game and experimentation perspectives.

We propose here a framework to analyze how MFA, their assets and their drawbacks are included into sustainability games. It is structured into two main parts.

3.1 Game analysis

In this part, we differentiate 3 categories:

Game objective. This category covers the intention of the authors when having this game played in terms of learning (L.) and expected participants (P.)
Learning (L.). In the learning category, we have gathered the games authors' statements into 8 specific learning goals when addressing MFAs:
- interdependencies ("interdep."): (related to systemic learning) exploring interdependencies in sectors, along a supply chain, …
- time: (related to systemic learning) exploring time interdependencies (short and long term decisions consequences),
- space: (related to systemic learning) exploring space interdependencies,
- relational: discovering stakeholders' representations of reality,
- sustainability: raising awareness of environmental disruptions,

- stress: raising urgency and stake in the decisions,
- uncertainty: on the information about the present and the future,
- circularity: on optimizing a supply chain by introducing loops in flows.

Within the games studied, the main learning objectives are to understand complexity (through experiencing the impact of interdependencies between sectors, space scales and time scales), sustainability issues and to make the participants realize how different representations of reality people can have and how this might affect collective decision.

Game support.
- Online: numeric interface.
- Board: physical interface.
- Hybrid: physical and numeric interfaces.

Game environment and roles. Description of the situation played (S.) and the stakeholders roles involved (R.).

3.2   Relationship to MFAs

Biophysical flow representation. What resources, pressures are involved and how are flows and stocks represented.

Biophysical resource representations. ("res. rep."): tokens, indicators, cards, ….

Biophysical flows representations. ("flows")

Material and energy resources are involved. As for the representations of these resources and flows, different strategies are used. First, some games hide the flows (and underlying models: black box effect) to the players and let them discover the system functioning through the impact their actions make on indicators. Some games let the biophysical resources be created and circulate between players without any focus on their transformations along the trip. As for resource transformation, they are involved in games pointing out a "supply chain" or "circularity" (CircusSChain [16] focuses on making a supply chain circular, Sanitation planning game focuses on the circularity of wastes, CAP'T'EN ValDech and CAP'T'EN Bois [11] involve biomass and wood supply chains).

Systemic learning. In what way is this game aimed at pointing out systemic effects on resources that might otherwise remain blind spots:

Interdependencies. ("I."): interdependencies in sectors (various activities/sectors related to each other), space scales, time scales (short and long terms).

How these interdependencies are pointed out. ("H."):
- "relational": discussions to realize the interdependence, trade-offs and shared interests.
- "trade-off": between indicators, most solutions found to improve one indicator are actually trade-offs when considering all of them.
- "game structure": the game structure (and associated flows) constraints the actions a player can take, and thus points out interdependencies.

Each of these games (but CircusSChain [16]) aims at proving how systemic thinking is important (consistent with the stated learning objectives), by putting the system under stress and forcing players to compromise. Yet, different strategies are used: some games directly use the flow structure, constraining players choice by the resource availability (token left) or pressure levels. A similar strategy is used through indicators: the constraint is not directly on the tokens availability but on sliders' choice to reach a chosen alternative in the feasible solution space left. Finally, and often used as the main strategy in nexus games, systemic learning is based upon the relationships between players: different roles involve different interests. Negotiations to improve one's interests lead to highlighting links between sectors and scales (links explicitly shown in the game or hidden in a computer code).

Decision framework. What actions are available and how do the players' decisions intersect with the biophysical structure of the game. In most of the games, players were entitled to individual actions with consequences on the collectivity. These actions mainly depended on roles and could be

- controlling the biophysical flows (transport, production, transformation, trade, consumption and waste),
- controlling the technology and infrastructures related to these flows (infrastructures and technology investments, infrastructures buildings),
- controlling the social structure of these flows (resource allocation policies, resource management policies, life-style policies).

Note that in each of the studied games, players are allowed to talk with each other and can thus collectively decide which individual actions each of them will take. In most of the games, socio-economic indicators have been added to force the integration of the biophysical structure in socio-environmental systems. Once again, the case of CircusSChain must be treated separately. The objective here is to optimize the supply chain by allowing its circularity, and is thus decorrelated from a real socio-environmental system.

Most physical (board) games disclose and share all information, whereas digital games can keep secret some flows, processes or individual capitals. Information disclosure is anyway a key factor in the decision patterns.

Link to data. How real the data involved in the games are. Different choices can be made here, compromising between intelligibility (people can imagine the data) , accuracy (the data chosen allow a correct simulation of the phenomena at stake) and playability :

- using real data ("real"): in Table 1, this feature has been automatically chosen without mentioning otherwise in the articles for online games. This solution allows for a quantitative description of the biophysical system. In most of the games, indicators are added to help players to imagine the data and make their trade-offs.

- using abstract discrete data: This solution is qualitative only and does not appear in the literature considered. The data is not related to reality. If the game might be simplified, the debriefing is then more complicated.
- using discrete data transformed from real data ("disc"): in Table 1, this feature has been automatically chosen without mentioning otherwise in the articles for board games. This solution allows for the use of tokens. However, this requires hard work to remain accurate while reducing different data (types and orders of magnitude) to small integers.

Note that in the games studied, we have found no purpose of pointing out data uncertainties.

4   Learning from field experimentations

In addition to literature analysis, we have conducted in this work three experiments to explore MFA and systemic based games as well as the use and impact of such models on participatory processes.

4.1   Creating a game focusing on the control of biophysical flows

Our first attempt consisted of the design of a game in which we copied a MFA structure to focus on systemic and biophysical coherence learning (spatial and sectors interdependencies) as well as sustainability issues, without introducing any money.

To this end, we chose to represent 4 territories sharing water and energy production, producing food (agriculture) and housing (wood and metals). Each territory has four slots to set up production or transformation industries. These slots take resources and transform them into other resources, GHG and pollution. The territories are related to each other through biophysical flows. To end with, each territory has work force units that must be fed and housed to be able to keep the facilities running.

We wanted to really focus on biophysical flows. Thus, we decided to represent every material and energy resource by tokens, being transformed during their journey along the different "supply chains". The systemic learning would then come through understanding how the chosen sectors were linked and how one territory could induce indirect pressures on another. The decision framework was mainly organizational: each player could decide what industry to set up in its territory and who he would trade with. Socio-economic indicators were introduced: the ability of each player to provide food and housing to its working force would determine a "social satisfaction". Finally, we fixed the numbers defining the efficiency of the different industries. We tried to choose them in coherence with reality but no real work has been done to transform continuous real data into small integers.

This first attempt to play with flows happened to be far too complex. Indeed, if the initial situation allowed each player to fulfill its needs, changing this initialization required complex computations, similar to the reconciliation process[2] run to fulfill missing data for real MFA. Some flows became unknown and others remained determined: the players thus had to solve a discrete optimization problem to fill the gaps with relevance given the admissible space left. This barrier might be overcome by introducing stocks, a better designed playing time sequence. Following the literature, we could also think of introducing a calculation spreadsheet to help players.
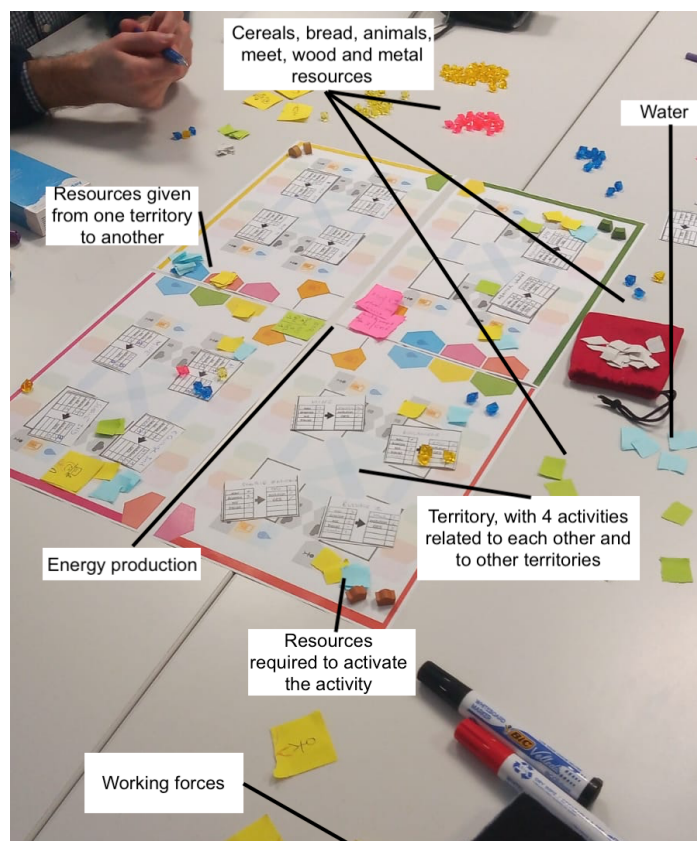

Fig. 1. First attempt to play with MFAs.

4.2 Creating games focusing on pointing out biophysical systemic effects

In our second attempt, we chose to focus on systemic learning rather than biophysical flows representation. We chose two systemic effects and designed a game to experience each.

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[2] Data reconciliation is used in MFA to translate incomplete and inconsistent data to flows respecting e.g., mass conservation [7].

The first game (called "Chicken Game" [4, 28]) aims at highlighting the geographic transfer of pressures. In this game, we follow the steps of making a roasted chicken, from the cultivation of soybeans in Brazil to the French supermarket. Each player represents a stage with its location and the pressures induced (land use, energy needs, water needs and greenhouse gas (GHG) emissions) and have information only about her/his step. One player plays the consumer. In the first phase of the game, the consumer walks up the production chain while the other players draw their way of representing the situation. In a second phase, the consumer goes back down the chain, collecting pieces materializing the different pressures and ends up in the supermarket with all the pressures induced on the chain.

This game represents a supply chain. The resource that is transformed (grain towards chicken) is materialized by a magic card. The pressures are tokens. The flows are represented by the consumer's journey from the end of the supply chain to its beginning and way back. The players do not have many decision possibilities: they can only draw the situations and guess the effects of this supply chain. As for the data, small integers (because pressures represented by tokens) have been chosen with respect to Life Cycle Analysis studies.

This game revealed that the process of transforming real data to small integers is a critical point. Indeed, the players couldn't project themselves in the game and discussed the realism of the settings instead of experiencing the pressure transfer effect. In MFA, several flow data are involved, sometimes with very different orders of magnitudes. Yet, "small flows" cannot always be neglected because of their relevance in the biophysical structure or their meaning in the socio-economical system. Thus, the game balancing process must be carefully chosen and strongly related to the test case considered.

In the second game (called "Cooperate or compete" [4, 29]) players must go through each round together by creating required products (3 different types, represented by the triangle, diamond and parallelogram). Each unit can be produced through 2 recipes, consuming different raw materials, obtained by exploiting a hexagonal territory. Some of them are renewable and others are not: the latter allow more efficient recipes, but they are depleting (obtained by a roll of the die, with increasing difficulty as the territory is exploited). Gradually deprived of these efficient recipes, players must fall back on renewable resources, leading to competition in their uses.

This game does not represent flows but focuses on the transformation process. The resources are tokens, used to create products. To avoid the real data barrier, the resources are here chosen abstracts. However, this complicates the way back to reality (thus the learning), and a special attention must be paid to the debriefing phase.
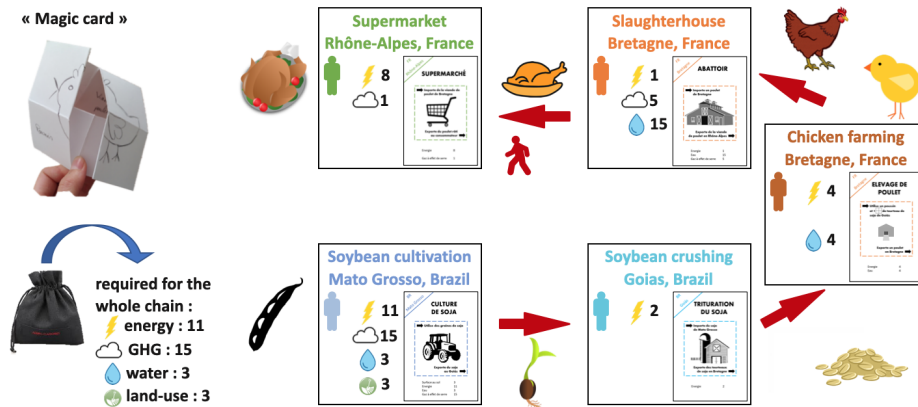
Fig. 2. Chicken game, going back the chain.

Fig. 3. Cooperate or compete.

4.3 Put energy flow analysis to the test on territorial consultation

To better understand how MFA can be related to stakeholders transforming territories, we also have animated three workshops with an energy flow analysis on the Pays Grand Briançonnais, composed of the Pays du Briançonnais, Écrins and Guillestrois-Queyras (France), on which operates a Pôle of Territorial and Rural Equilibrium (PETR). This territory will soon be involved in a participatory resource management process. Indeed, this mountain territory is the head of the Durance basin, with a strong hydroelectric potential and contains biodiversity reserves (Parc Naturel des Écrins, Regional Park of Queyras, Natura 2000 zones). The tourist economy is strong there, summer and winter (skiing). We have been asked by the president of the PETR to structure an "upstream" debate between the various

stakeholders, and to reduce the various stakeholders, and to reduce the contentious blockages.

During three workshops (they were only preliminary experiments and further work is expected), we gave the participants (11 people in total) an energy flow analysis based on a diagnosis realized for the Plan Climat Air Énergie Territoire (PCAET). Already pointing out some interdependence, people asked about more accurate data. They especially required information on specific sectors, on different space scales (where do the flows exactly come from or go to, when imported to or exported from the territory, what is my contribution in this analysis), time scales (the diagram was for a year, but what about for a month, a wee, a season). They also asked for a socio-economic analysis to be coupled to this study. In particular, besides biophysical flows, knowing the actors controlling them and the levers of action to be associated. These first tests have therefore confirmed the ability of the MFAs to enable systemic analysis and the lack of a decision framework to really make the knowledge operable.
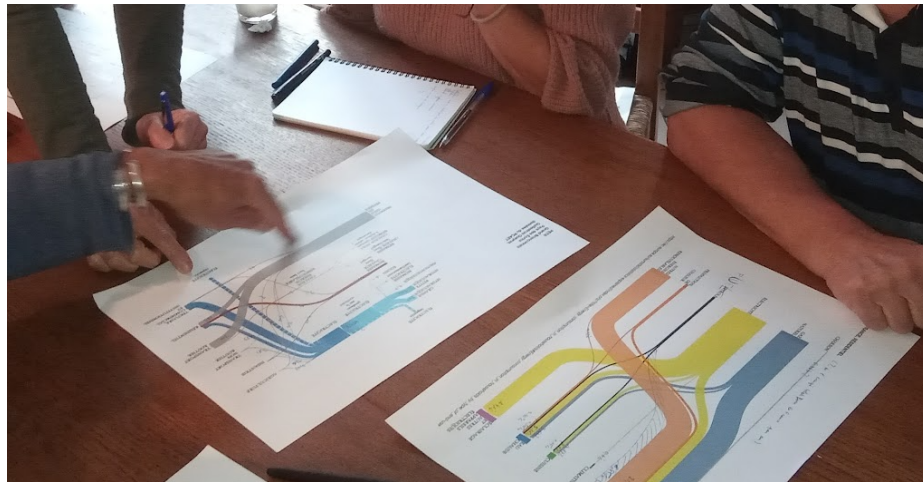

Fig. 4. Workshop session, presenting an energy flow analysis (December 2022).

5   Analysis

Based on the literature and on these exploratory experiments, we infer the following insights about playing with biophysical flows in transition towards sustainability. We focus here on a board game, in which resources would be represented by tokens.

There is a critical relationship between the biophysical structure representation and the social decision framework, materialized in the players' actions:
- for the biophysical structure, players can control various resource flows intensities directly (through stocks control) or indirectly through the

transformation processes (infrastructures, technology). This control can be individual and thus distributed between players, or collective, requiring players to negotiate and decide together.

- for the social and institutional structure, players choose regulation flow rules, restricting or enabling the actions they can make on the biophysical structure. Once again, this control can be individual (one player can control distribution policies related to one resource) but are mostly collective.

There are also drivers on which the players cannot act. In sustainability contexts especially, the complex dynamics due to systemic effects can counterfact the players' intention.

This decision framework is related to the information flow in the game. Indeed, to avoid complicated discrete reconciliation, players must pre-decide and share options for resource flows. Actuation comes only after the use decisions were taken "downstream" by the "consumers". Negotiation can occur, as in real life. It requires a clear time sequence regulating an information cycle before action.

Toward a relevant game design, the users, for the goals categorized in [5], would need to visualize stocks and flows, to decide and control them, under explicit social norms, to elicit and combine constraints related to various resources, to project future transformations, to relate this to various scales starting from their individual level. Therefore we propose the following alternative apparatus including the key useful features of MFA, but extended to support transition.

## 6 TransKey: a prototype model and game for transition support

After this analysis, we have designed a generic model to support new transition game design, adapted from the previous MFA games and goals. The target features are : representing multiple resource stocks and flows, their dynamics, stakeholders' constraints and control, exogenous drivers, multi-scale representations, player friendliness, data fitting when required, connecting material and digital version. The resulting structure is described in Figure 5.

TransKey model and game
TransKey = {Resources, Stocks, Processes, Taps, Network, Tapholders, Control Matrix, Control Rules, Payoff, Activation Scheme}
- *Resources* are any consumable and transferable resource, good or product.
- *Stocks* are specified for each resource. Many stocks can exist for the same.
- *Processes* carry, consume and produce various resources, for which a Process Function specifies the transformations and their conditions.
- *Taps* control the outflows of stocks and the activation ratio of processes.

- The *Network* is the overall structure of interaction between components.
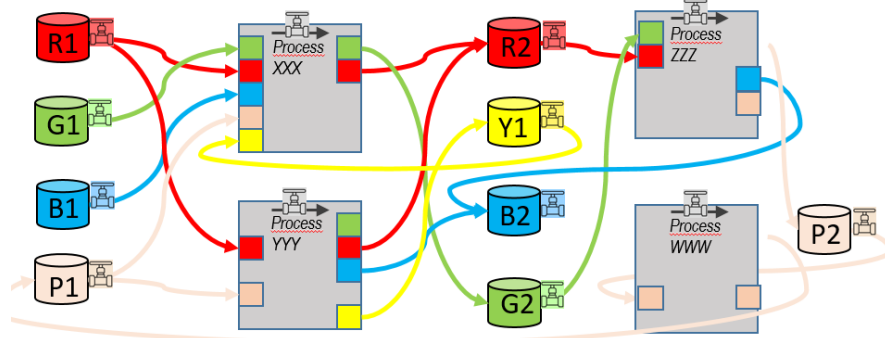
Colored arrows only show the topology of connections. The process WWW is a "pure transport flow", moving one resource from stock P2 to stock P1, at no extra cost with any other resource.

- *Tapholders* are social actors (persons or groups) animated by players or the game manager, who "own" some stocks, control the taps and discuss rules.

The process functions *pf* should be of the form:

$$O_{pf}(t) = pf(I_{pf}(t\text{-}\Delta t),t,c_{pf}(t))$$

where *t* is time, $O_{pf}(t)$ is the (discrete or continuous) vector of produced resources at discrete time *t (*round), $I_{pf}(t\text{-}\Delta t)$ the vector of the input resource at time *(t-Δt)* with *Δt* a delay (equals 0, 1 or 2: a delay of 0 to 2 rounds), and $c_{pf}(t)$ the control over this process at time *t*. Autonomous processes without control exist.

Social actuation and regulation: Stocks' and processes' taps are controlled by zero to many tapholders defined in a *control matrix*. For any "tap group", the "*control rules*" are specified, as mandatory rules (from the model settings) or as players' choice (dynamic : mean rule, vote, random, deliberation, etc).

Tap / Tapholder	TH1	TH2	TH3	TH4	TH5
R1			1	1	1
G1		1	1		
B1					
P1	1				
XXX				1	1
YYY				1	
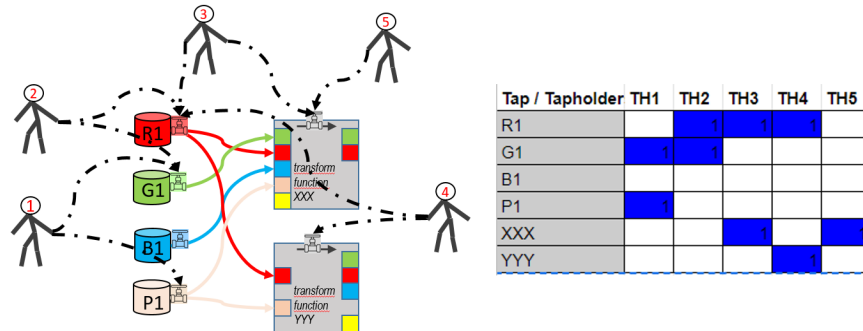
Each tapholder or group has a *payoff function* depending on some stocks, single- or multi-valued (e.g. current state of one stock, set of values of 2 stocks, weighted sum of 3 stocks, growth, etc).

Tapholders' Activity & Dynamics :

1. Deciding or adjusting each "tap control rule", or keeping it as it is
2. Deciding and sharing stock' tap output "offers" by each stock tap group
3. By process tap, tapholders propose individually their control preference for tap, based on the upstream flow information.
4. The process tap group applies the "tap control rule" to set the process ratio, and the outputs. It computes the input resource actually consumed.
5. The new stocks are updated (subtracting and adding).
6. The tapholders evaluate their payoff.
7. Tap groups assess and express "demands" for incoming resource flows.
8. (option) Any tapholder can ask to enter any tap group, who accepts or not.
9. (option) Tapholders can activate new processes chosen in a set. A creation cost has to be "paid" from the tapholder' controlled stocks.

The dynamic ends after some rounds or when a given payoff is reached.

Figure 5 : The TransKey model specification

Conclusion

If biophysical accounting and especially MFAs are undoubtedly useful to design transitions, they remain expert tools that cannot be manipulated easily by stakeholders transforming their territories. One way to better understand the use and impact of these models would be to make people play with them during serious games. The literature gives various insights on how to play with biophysical flows, and especially about how to represent them and which control players have on them. We supplemented this work by three field experiments which pointed out the importance of data, its accuracy and its transformation from real data to small integers. It once again pointed out the care to be taken in designing the decision framework. Indeed, to make sure players can build biophysically consistent scenarios, the playing sequence involving actions and information flows is crucial. From this study, a new game structure has been sketched and further work will include a full implemented design, putting them to the tests and analyzing people's reactions to better understand how MFAs could be used to support stakeholders in transition territories.

Table 1. Table captions should be placed above the tables ("abst": abstract., "coll.": collective, "disc.": discrete, "ind.": individual, "interdep.": interdependency, "res.": resource, "rep.": representation, "SE": socio-economic, "spatial.": spatialized, "stkh.": stakeholders)

Game/projet (and support)	Goal	Game environment and roles	Biophysical flows representation	Systemic	Decision framework	Link to data
Wat-A-Game toolkit + 180 offspring [1, 10] games (board, multiplayer)	L. interdep. space. relational. sustain. P. everyone	S. directed graph with places and actions - any discrete resource dynamic & sharing R. any type	Res. rep: colored tokens for representation of each resource Flows: movable card connectors on which the tokens circulate	I. Multi-functional exchange and production system H. Relational, trade-off	Ind. actuation of "action cards" transforming res.. Coll. decision on res. management and sharing. SE indicators (with and without money).	Disc.
The Nexus Game [20] (board) (multiplayer)	L. interdep., relational. P. policy makers, professionals, students.	S. 2 countries sharing a river. R. Ministers (decide) journalist (observe).	Res. rep: tokens (water, food, energy, pollution). Flows: only water flows between players. No focus on res. transformation.	I. Sectors (competition in the use of resources), space, time. H. Relational.	Ind. (sectorial) actions (res. allocation, infrastructures policies). SE indicators (with money).	Disc.
Sim4Nexus [27] (online) (multiplayer)	L. interdep., relational, time. P. everyone.	S. Abst. spatial. territory. R. Managers of each sector.	Res. rep: indicators (food, energy, water, climate, land use). Flows: hidden in the computer code (system dynamics). No focus on res. transformation.	I. Sectors, time. H. Relational, trade-off.	Ind. (sectorial) actions (policies). SE indicators (with money).	Real.

Magic nexus [25] (online) (one player / multiplayer)	L. interdep., sustainability. P. everyone.	S. 1 to 4 regions . R. Managers of each region.	Res. rep: indicators (food, energy, footprints, water and land use limits). Flows: hidden in the computer code. No focus on res. transformation.	I. Sectors, spatial. H. Relational, trade-off.	Ind. (regional) actions (production, consumption, import of food and energy). Real.
PostFossil Cities [22, 24] (hybrid) (multiplayer)	L. sustainability, stress. P. everyone.	S. City. R. 7 roles of relevant societal stkh (politicians, population, investors, …)	Res. rep: indicators. Flows: hidden in the computer code (based on an MFA model). No focus on res. transformation.	I. Sectors. H. Relational.	Ind. actions (technology or life-style on energy, building and transport sectors). Real.
CircusSChain (board, + calculation spreadsheet) (multiplayer)	L. interdep., sustainability, circularity. P. students and professionals.	S. generic supply chain. R. Different actors on the supply chain.	Res. rep: tokens (material, GHG). Flows: tokens moving along the chain, with material transformation.	I. No (only one sector).	Control information flows. Decide loops to introduce in the supply chain (coll. or not). SE indicators (with money). Disc.
Sanitation planning game [15] (board) (multiplayer)	L. interdep., relational. P. everyone.	S. Abst. spatial. territory. R. Various stkh. related to sanitation (roles translated at each round).	Res. rep: cards (waste, food, NPK), indicators (water quality). Flows: dice allow material transformation.	I. Sectors. H. Relational.	Ind. (role) actions (build, transform resource) and coll. action (joint policy). SE indicators (with money). Disc.

CAP'T'EN ValDech [11] (board) (multiplayer)	L. sustainability, relational. P. everyone.	S. Abst. spatial. territory R. farmers, institutions.	Res. rep: tokens (biomass materials), indicators (GHG, energy, agronomy). Flows: material transformation and trade.	I. Sectors. H. Game structure, relational.	Ind. (roles) actions (transform resource, trade, management policies). SE indicators (with money).	Disc.
CAP'T'EN Bois [11] (board game) (multiplayer)	L. sustainability, relational. P. everyone.	S. Abst. spatial. territory R. craftsman, businessman, manager, park, transporter, builder, sawyer, operator.	Res. rep: tokens (biomass materials), indicators (GHG, energy, forestry). Flows: material transformation and trade.	I. Sectors (along the supply chain). H. Game structure, relational.	Ind. (roles) actions (transform resource, trade, build, transport). SE indicators (with money).	Disc.
LIPTAKOR [13] (board game) (multiplayer)	L. sustainability, interdep., relational. P. inhabitants of villages of gold-digging in Niger.	S. Spatial. territory related to the test case. R. Various stkh.	Res. rep: token (water, gold, wind, … all resources), indicators (pollution). Flows: water flow and trade between players. No focus on res. transformation.	I. Sectors. H. Game structure, relational.	Ind. actions (get resource, trade, invest in technology) SE indicators (with money) and biodiversity.	Disc.

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