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Decision rules and assumptions in overexploitation of renewable resources

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Short abstract

Behavior of actors within their specific socio-economic environments differs with respect to their rationality, intentions and perceptions, which results in different decision rules and thus different impacts on the dynamics of the system of which they are part.

In the area of resource exploitation, fieldwork is an extremely rich source for actual knowledge building. In addition to this quasi-empirical cases can provide insights through analysis and *comparing* among different set of assumptions of the agents and/or of the underlying structures. This should contribute to our understanding of behavioral modes of various classes of systems related to resource exploitation. Furthermore, analysis of impacts of oversimplified assumptions by agents with decision power could be applied for educational purposes as well. In this session we construct a simple predator-prey based reference model as a basis for analysis of thought experiments in the area of exploitation of limited, renewable, resources. We apply a case study from the existing literature for drawing the initial contours.

This document contains motivation, objective, conceptual model, initial outcomes of sample case and future objectives are described. Detailed model formulation is provided as well. This work is in progress.

Keywords: “Resource Dynamics, Structural Analysis, Policy Analysis, Sustainability”

Motivation

Attention for “Resource Dynamics” related topics has been growing increasingly over the years, both in the academic world as well as in the public opinion. At the same time, more natural resources get closer to the lower limits of sustainable levels, while locally and globally population increases, supply and demand processes become more complex and markets and responsibilities are less transparent.

In his famous ‘69 article “The Tragedy of the Commons”[1], Hardin describes the *inevitability* of the erosion of common properties. In his ‘80 article of “Ecolate View of the Human Predicament”[2] he adds to his analysis and calls for a new level of education, at which a person achieves a working understanding of the complexities of the world (in particular on phenomena as carrying capacity, redistribution, and comparing behavior in systems of “privatism”, socialism” and “commonism”).

Theoretical and experimental descriptions of Commons are innumerous (see for instance Hess [3]). Many of those works are focused on confirming the static lock-in concept or are dedicated to finding a solution for a specific empirical case. In [4, 5], Ostrom thoroughly analyses results of various *field-studies* and *experiments* in order to understand different “modes of rationality of actors”: what are the intentions of people acting within the system, how do they co-operate to? She concludes by arguing for “adaptive self-organizing decentralized policies”.

In his well known article “The Economics of Overexploitation (1973)”[6], Clark goes beyond the problems of the commons. By distinguishing between Rent and Value maximization, he shows that even in the case of Private ownership “*Extinction will indeed occur as a result of the maximization of present value, whenever* d *[the discount rate] is larger than 2 times the maximum reproductive potential of the population*”. The conclusion is “to extinct or not to extinct”.
This article is an extremely important theoretical foundation for understanding the *concept* of “overexploitation”. In fact, Ostrom argues that in wrongly constructed Common Resource Pools, this type of behavior is an important sources of over-exploitation[5]. But while Clark’s paper, though based on a real case, had a theoretically construction, it was and still is widely cited as the “truth”[7]. The real world is more complex, perceptions change over time, and people behave not purely rational.

At about the same time as Hardin, in 1971, in “Counterintuitive Behavior” [8] Forrester cautions among others for the lack of understanding of social systems by policy makers, and the dangers of misperception of feedback in decision making processes, placing it in a broader perspective than only the commons. In fact, this problem is not less actual (Sterman [9]).
System Dynamics is perfectly suited to provide insight in the complexity and dynamics in limited resources management, proven by the broad perspective on world modeling [8, 10-13], and on the other hand, through extensive experiments in very specific resource management cases (not commons related), lot’s of insight has been gained in the behavior of humans confronted with these limitations, showing continuous overexploitation (Moxnes in [14, 15] on Fishery and Reindeer) and for conceptual analysis in (for instance [11, 16, 17]). In [18], a generalized framework is developed, at a macro-economic level of detail.

The following list, extracted from the articles mentioned above, sums-up typical issues when confronted with management of limited resources

Misinterpretation of net-growth curves of the resources with implications for harvesting decision rules; Incremental improvement policies (shifting the burden); unstable equilibria in systems: role of small disturbances; Impact of technology development and other policies; Management of resources through commons versus private property; Chasing short term goals and risk-averseness for long-run benefits; Internalizing of costs (both towards current as to future generations); Incremental, reactionary versus adaptive, self-organizational policies and technologies; Delays and misinterpretation of information; Complex, rigid policies; Ignoring dynamics: treat seemingly “out of control parameters” as frozen; Eroding goals.

Much of this can be brought to the *Misperception of feedback and delays.*
Moxnes [15] argues for more research for management of private and common resources, “to clarify mental models, heuristics, to contribute to the understanding of bio-economics as well as misperceptions of feedback in general”.

We assume that although each case is different, restriction to a limited set of modes of behavior is useful for capture the problematique on resource dynamics. This leads to the hypothesis that one flexible model can bridge between theory and the many empirical field studies. The analysis of and comparison among the individual quasi-experimental studies could contribute to a further understanding in the root causes of the problems for families of cases.

Objective and approach

The goal is to develop a stylized reference model, simple enough for understanding various dynamics, complete enough to cover various empirical cases, that contain the “erratic-behavior-modes” described above.
Existing predator prey concepts are used as a basis and adopted to serve for these general cases. Here (in this poster session) we will present a simple reference model in the form of a causal loop diagram. We develop a case, based on the non System Dynamics Clark article discussed above[6].
Discussion of and learning from application of that case, will, will provide a first input for the development of a more complete reference model, after which it may evolve through submission to other cases.
Finally we show that a dynamic and richer approach in terms of behavior, to a theoretical problem statement as that of the Clark article increases our understanding of the structure of the problem

Structural Framework

Reference Modes:
Obvious dynamics resulting from the problems described above, are overshoot and collapse (e.g. the Kaibab-deer around 1930 ([19]),and furu in Lake Victoria around 1988 ([20])).
Other managerial problems are sheer extinction of a specific resource in other words overshoot and collapse of human activities itself, on a specific resource and finally “shifting the burden” [8, 10], where efficiency in exploitation of one resource, results to creation of a problem at the next resource. This might lead to oscillatory processes.
In other words, a basic model should be able to capture gradual extinction, oscillation and overshoot and collapse of a predator and prey population.

Organizing Concepts

In general, we assume that predator activity is directly driven by its utilized capacity to harvest. Evaluation of success by the predator, results in decision to harvest more or less (for instance retreat from exploitation is a possible choice), in other words to adjust dedicated capacity. Actual success depends on the health of the predator, but fore mostly on the conditions of the prey population.

Carrying capacity of the prey (or resource) can be affected in the first place by its own density, in the second place could be impacted by too much activity (increased pressure) from outside. The evaluation method for success depends on the environment and the rationality of the predator (or instance from reactive to adaptive or systemic). Intensions, perceptions & information availability and rationality determine the decisions for management of the resource. Mismanagement of the resource often results from well-intended, but erroneous approaches to correct resource populations(and optimize for own purpose).

Description of Basic Mechanisms

In the description of the basic conceptual structures, main stocks will be highlighted, but flows are omitted:

Predator Prey Model

As starting point we take a typical Predator-Prey Model (Fig 1. – see for instance [19, 21]).

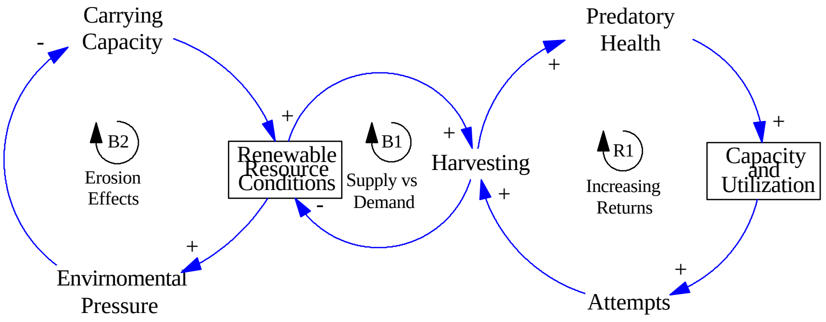


Fig1. Basic Predator Prey Mechanism.

Structural behavior as phase-shifted oscillations between predator-prey populations can be explained by through this construction, especially when we take random fluctuations in net birth rates into account.

In the case of too much pressure on the environment by the resource (e.g. overcrowding), the carrying capacity will be decreased (Erosion.B2), structurally reducing the natural growth potential of the resource. This can occur if the pray on the right hand sight is suddenly removed or strongly reduced.

In Figure 2, we see a construction, for a more diverse and complex predator-prey environment. Competition with other predator (populations) is introduced and the predator is assumed to exhibit more applicable intelligence: observations and judgment is done towards opportunity from a perceived resource condition, resulting in the first place in competitive predators (B3).

In this case reduced success in terms of health (resulting from lower return on harvest attempts), or effects of a reduced opportunity leads the to search for different preys: adjust supply demand to supply (B4). However, if alternatives are not available, reduction of capacity (i.e. population or long-term weakness) will balance the situation (B2 – Decreasing Returns and R1- Effectiveness). In some cases, increased activity of the predator may impact the environment and thus the carrying capacity of the prey (B5b).

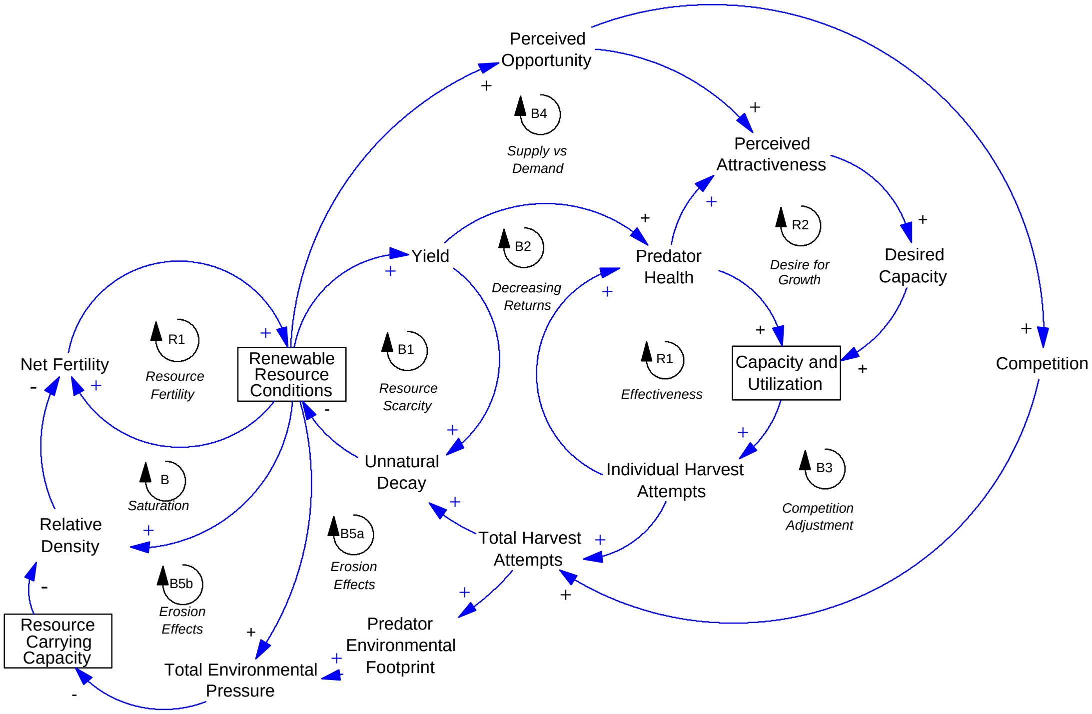


Fig 2: Predator – Prey in competitive multi-environment.

2) Adjustment for Human Predator Prey Model

We assume humans behave conform the model of above, except for a few fundamental differences:

- For judging attractiveness (*perceived attractiveness*), humans will look towards the future (i.e. integrate over current perceptions and historic events) and sideways (study of competition, for comparing alternatives (but not necessarily in a correct way). Attractiveness valuation processes are mostly economically grounded and are based on expected financial performance “perceived future benefits” combined with current health assessment (for instance cost from capacity and utilization and benefits from harvesting). The exact decision rules of future benefits depend on the socio-economic values of the environment. This is a combination of assumptions on

“Rationality (or Bounded-ness of it), Social pressures against exploiting scarce resources, taxation rules and stakeholder and ownership constructions (See for instance discussions Ostrom [5] (rationality and intensions), Moxnes [15] (financial rules, rationality and intensions), Clark [6] (financial rules)). Ownership construction can sometimes be related to the number of competitors or can be dependent on the total number of stakeholders. In the later case, those costs of exploiting can be considered being only dependent on the state of the resource (or perceived state) and very low. Exact decision rules and organizational construction will become explicit for the different models.

- “Outsourcing” of predation, often performed by “companies”. This can lead to consolidation of harvesting. In order to increase yield, and given our abilities, methods are increasingly built on technology (either through supporting tools or complex processes or both). Complexity and economies of scale, implies delays in building and especially decreasing capacity[22]. It is not by definition the case that human perception will take this kind of delays into account while performing attractiveness valuation. Complexity leads to perception delays and errors in measuring resource quantities.
- Related to the above, instead of pure health assessment of the predator population, in order to compare alternatives, valuation of successes and failures are based on complex socio-economic calculations and assumptions. There are various ways of rationalizing the *expected* values into decision rules: this depends on the socio-economic structure of the predator and its environment. For sure, lot’s of information is needed to process these expected values.

The result is a general, simplistic conceptual model for humans acting in resource dynamics: see figure 3. The conceptual model is revised as indicated.

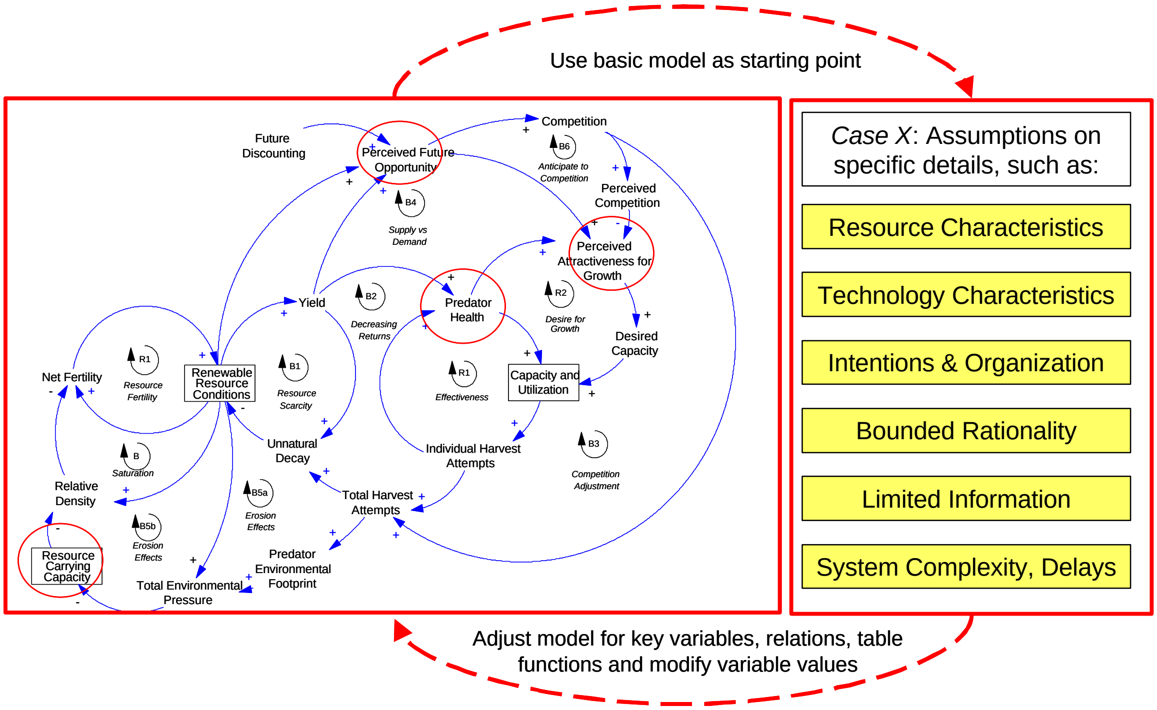


Fig 3: Reference Mechanism for Resource Management Mechanism – based on Predator Prey model.

For each individual model, basic equations will be taken over and based on assumptions on resource characteristics, technology characteristics human intentions, bounded rationality of various actors, limited information available to the actors and certain structural additions, the reference model is adjusted.

Important differences with the animal case are the increased number of delays in the information, decision and adjustment parameters, resulting from an increased “complexity” of the environment.

Note that the “Renewable Resource conditions” function as a carrying capacity for the human predators in a certain type of business. Overexploitation and extinction of the resource and next collapse in the economic capacity, is under many circumstances quite feasible: the reinforcing loop of increasing revenues (R1) and availability of resources, will lead to increased exploitation, by an increased number of competitors (if not private ownership, while choices to reduces utilization and capacity are made on a micro-economic (Individual) scale, take time, not considered in the building of capacity (B5,B4).

For the actual analysis individual cases, we add the specific decision rules for “different hypothetical realities”, impacting perceived future benefits, attractiveness evaluation, desired capacity building, delays and impact on environmental pressure. Finally we will use “reasonable estimates” for the various parameter-values (e.g. time delays).

Case: Clark’s Economics of Overexploitation

Introduction

Mathematician Colin Clark[6] showed, that exploitation of slow-growing resource-populations (relative to depreciation rate), even in the case of private ownership, would naturally lead to severe depletion and could even to their extinction. His approach is that of calculating the long-run static equilibrium state, in the case net present value maximization. This assumes a highly rational, purely economic driven decision-rule, evaluated within a more complex environment. Here we go along with his whaling fishery example. However, naturally large capacities and delays in building and reducing play an important role. Dynamics in the Carrying Capacity of the depleted resource is not considered as relevant in this case.

It is not he objective to explore all dynamics, rather to assess the usefulness of this approach, understand the limitations and discuss modifications. We do state that this kind of rational should be dealt with, when analyzing behavior.

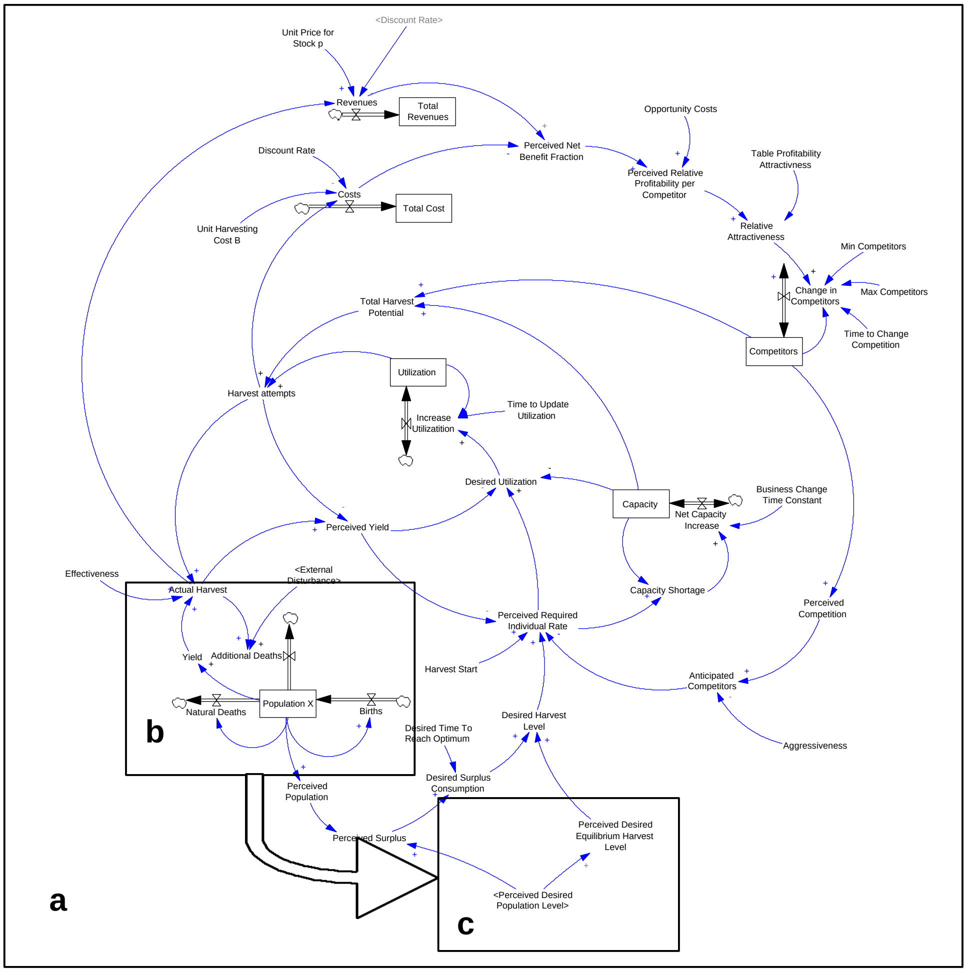
Main assumptions

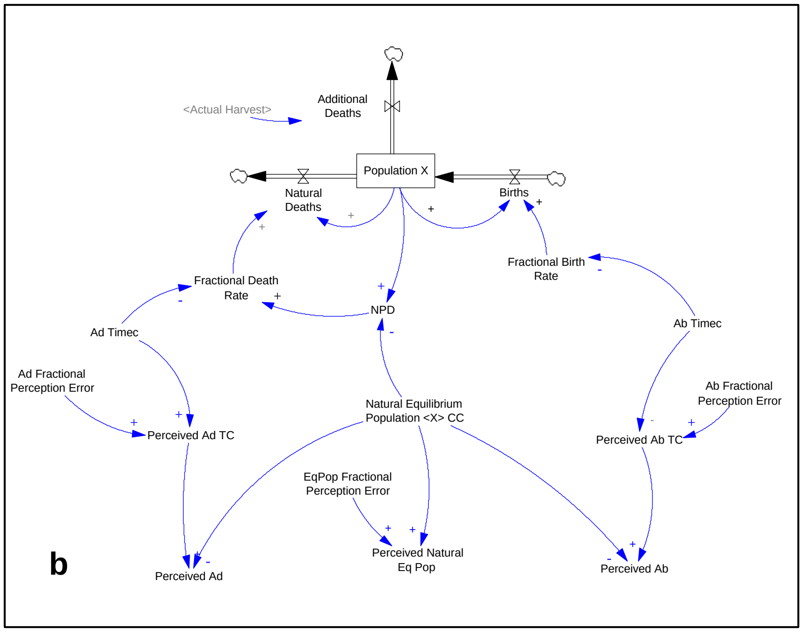
The Clark model is an equilibrium calculation. It uses exploitation of the “Blue Wale” as a reference. Since it assumes very rational actors, the assumptions are quite extreme, but for the base-case we will adhere as much as possible to these numerical and analytical assumptions. The Clark article describes two cases: Rent maximization and (Net Present) Value Maximization. Below follows the set of assumptions for both, next we will describe the deviations from the Clark model to introduce the necessary dynamics for the base-case, later relaxations will be described in the analysis.

Segment	Assumptions Case A Rent Maximization	Assumptions Case B Value Maximization
Resource Characteristics	Standard population dynamics is assumed. Clarks' logistic equation of theoretical biology is converted to more explicit System Dynamics equations. Crowding effects do not affect birth rates, while death fractions increase linearly with population. In normal population density, reproduction (and death) is every year. Maximum reproductive potential is about 10%. For the base case, both yield and estimated yield are a linear function of density (Max(Population/Relative Density, Relative Density).	
Technology Characteristics	We assume a capital and technology intensive environment, where business decisions and actual changes on capacity changes are in the order of months (for instance the "Business Change Time Constant" = 3 month). Competition time constants to enter and leave are 4 Months.	
Human Intention and organization	Humans are totally economically driven, behave individually; try to optimize the rent, through a Rent Maximization Function.	Humans are totally economically driven, behave individually; continuous Net Present Value Maximization of activity, at least perception of it. Relevant time constant for this are time horizon for discounting TH, population data, estimated time to reach optimum T.
Bounded Rationality	Actors understand population dynamics. Competition and time delays are acknowledged, but not necessarily fully perceived (either misjudgment or through aggressive policies to be the first) In case of perceived overcapacity, utilization is reduced. Desired capacity is matched with the expected capacity needed for that moment in time. Competitors respond solely to perceived profitability (versus opportunity costs).	
(Limited) Information	People collect all information required for their intentions, but can make misjudgments on the numbers of population, population time constants and necessary time to reach optimum.	
System Complexity, Delays	Perception of population, yield, and profitability is smoothed to one month. We assume that "Health", or in this case "Profitability", does not effect the yield (effectiveness is constant). Resource population does affect yield. Carrying capacity of the resource is not endogenously affected. For simplicity, there are no fixed costs (e.g. capacity holding cost), but agents are assumed to have incentives to hold capacity at the optimum level.	

Model

This results in the following (simplified) (a) model; (b) resource population dynamics and (c) harvest rate decision model. (b) Shown in detail





Full model documentation can be found in the appendix.
Here follows a description of the most important assumptions or differences with Clark:

Time Delays

We assume time delays in every decision process, which are not captured in Clark's static equilibrium.

Resource Dynamics

Clark uses for the net recruitment: $f_c(x) = A*x*(<x>-x)$,

Where
A = net birth constant of the logistic equation of theoretical biology [1/pop*tu]
<x> = natural equilibrium population [pop] [23]
x = actual population [pop]

In this model we rewrite this into the more general: $f(x) = (FBR-FDR)x$

where
FBR = A_b (Fractional Birth Rate) [1/tu]
FDR = A_d*x*NPD (Fractional Death Rate) [1/tu]
A_b = birth time constant [tu]
A_d = death time constant [tu]
NPD = Normalized Population density = x/<x>

So for table function have been used, instead analytically solvable formula's
Note: this results in a population that has no minimum level, implying that the population will always recover, if harvesting stops. This is clearly not a realistic assumption. It can easily be relaxed.

Rent Maximization

An actor maximizes the following function:

$$R_p - C_p = p*f_p(x_p) - B*h(x_p) \qquad \text{F.1}$$

Where:
R_p = perceived Revenue [\$/tu]
C_p = perceived Costs [\$/tu]
$f_p(x_p)$ = perceived net recruitment function of the perceived population, where all factors will be labeled with a p index, freely modifiable [pop/tu]
x_p = perceived population of the resource [pop]
p = unit price [\$/pop]
B = unit harvesting costs [\$/pop], normalized at NPD = 1.
$h_p(x_p)$ = effective harvest attempts needed = $f_p(x)/y_p$ [pop/tu]
y_p = perceived yield = 1/NPD [dmnl]

F.1 yields an (part of model inset b) analytical solution, of which the inputs are p, B, A_{bp}, A_{dp} and $<x>_p$

In the case that all actual values are equal to the perceived values and $A_d = A_b$ our perceived rent maximizing population X_{prm} is equal to Clark's solution X_{crm}:

$X_{prm} = X_{crm} = <x>/2*(1+B/p)$,

Note that this is higher than the maximal sustainable yield (the population where the net recruitment is at its maximum). The actor assumes it will catch the "optimal value", calculates the effort and optimizes this function and finally calculates the desired harvest rate:

$f_{prm} = f_{prm}(x_{prm})$

As can be seen, *as long as perception errors are exogenous*, the rent maximizing function is not endogenous. However, one could easily expect situations where expected values of fuzzy values of natural population. In that case this part would contribute to dynamics issues as well.

Actual exploitation is this f_{prm} plus the surplus population divided by the expected time to reach the equilibrium population

Throughout the base-case analysis p will be set to 1 and B to .5 [\$/pop] unless other stated.

Value Maximization

Value maximization occurs, requires two population level definitions:

ES = Expendable surplus = part of fertility, whose emplaced value is less than the liquidation value.

CF = Conservable flow = that portion of fertility of which the emplacement value is greater than the liquidation value.

This results in maximizing the two complementary values:

With P = R– C (see Rent part)

P_{CF} = INTEGRATE($P(x_{pmv})*\exp(-\delta*t);0;\infty$)

Where

δ = Discount rate [1/tu]

x_{pmv} = perceived maximum value population [pop]

$P_{ES} = p(x_{p0} - x_{pmv})$ – INTEGRATE($C_c(x);x_{pmv};x_{p0}$) = $B*\log(x_{p0}+1/(x_{pmv}+1)/<x>$

Where

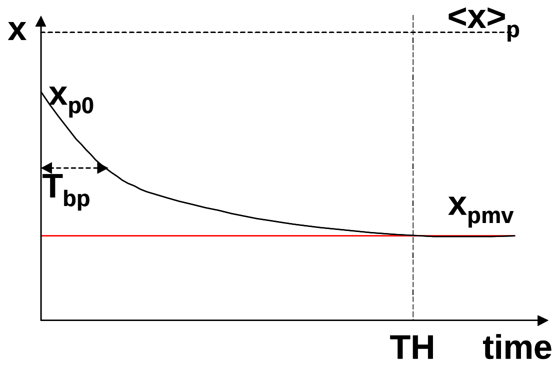
x_{p0} = perceived current population [pop]

C_c = B/(X+1) Clarks modification of the cost function [$/Whale]

Maximizing the total present value (Max(P_{ES}+ P_{ES}) with respect to x_{pmv} would yield the maximized solution.

We add the following modifications:

- It takes time to modify the capacity to (Business Time Constant). Agents take that constraint into account when calculating their perceived maximum value (but do not optimize that; agents can make a perception error in this time). See Figure. The result is that the P_{ES} function must be integrated over time as well, where x and f(x) depend on the time and the expected time to close the gap. This seems to be quite relevant (especially when holding cost are taken into account).
- Effectively, total time horizon is limited, so it could be that value is maximized over a much shorter time span (instead of infinity).
- People expect that the yield relates to the current yield
- Perceived values are input, not actual values.



Resulting optimization formula can be found in the documentation. The resulting function is more complex than that of Clark.

Resulting inputs: $<x>_p$, TH, T_{bp}, A_{pb}, A_{pd}, X_{p0}

Here definitely, we deal with endogenous factors (as X_{p0}).

Competition

Clark assumes individual exploitation of resources only. We add the possibility for competition, to analyze those effects in certain scenarios effects of competition. Competitors act upon the actual perceived profit function. There is a smooth in perception. If profitability is higher than actual opportunity costs, competition will increase, otherwise it will decrease. Competition can vary between 1 and a maximum population.

Competition doubling time = Competition half-life time ~ 4 Months.

Individual actors can have limited perception or intentionally ignore part of the competition (aggressive exploitation). They will maximize their rent with respect to that assumption.

Harvest Activity

It is important to note that in the base case the actual yield is assumed to be in conform with that of Clarks assumption, directly proportional to the Normalized population density (NPD). In later stages, the advantages of System Dynamics will be used to test the impact of differences between the agent's assumptions on the yield, forming a base for its mental and more simplified economic model and actual yield population dynamics. The same holds for agents assumptions on resource dynamics parameters.

Comment on expected outcomes

Clarks' key outcome is that in the case of value maximization, Extinction will occur if and only if:

- $\delta > f'(0)$ and
- $p > B$

, where f'(0) is the maximum reproductive potential.

It turns out that that these conditions still guide the dynamics in the case of our assumptions, but through the dynamic approach, many interesting behavior modes are added to it, without making the model more complex, than basically needed to describe Clarks' case.

Analysis

Below we can find some preliminary results and discussion of the runs, compared to the Clark model.

A) Rent Maximization

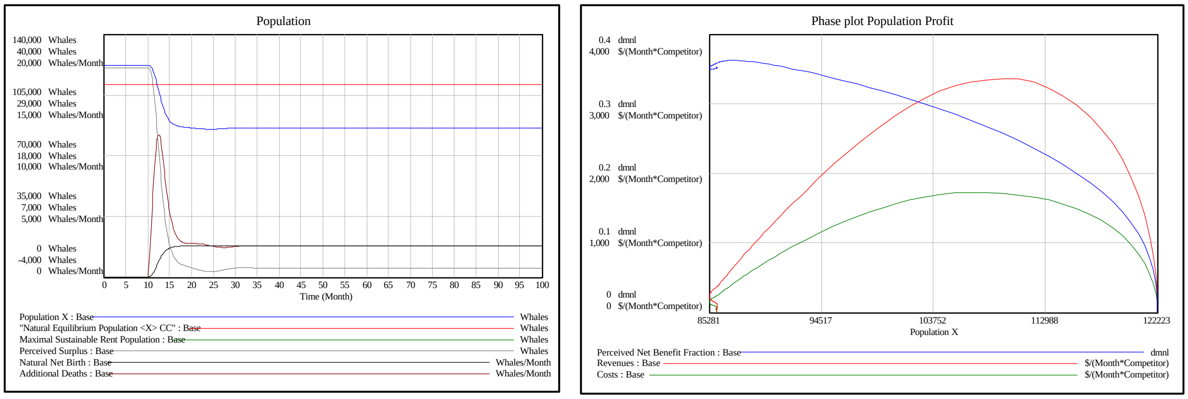


Figure A.1) Base-run: individual rent maximization

Population dynamics and perceived surplus (left) and actual rent for individual actor (right) in base run. As we can see in the left graph, the individual manages to achieve the population equilibrium level, which is about 92000 whales, conform Clarks' rent formula. This equilibrium level will always be above than and the maximum yield population; extinction will not occur.

On the right, the "population-rent phase plot" shows that the equilibrium value indeed represents a rent-maximizing situation.

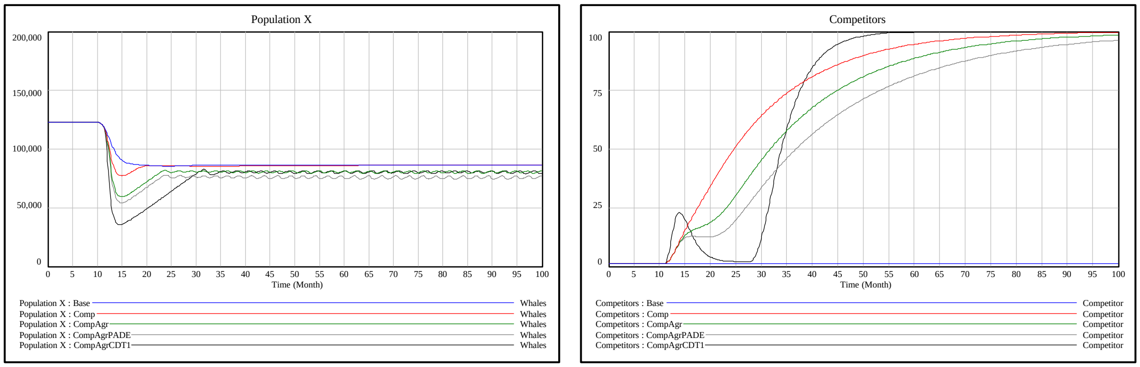


Figure A.2) rent maximization - alternative scenarios

Resource population and Competition shown for different scenarios: base case, Full competition allowed (Comp), Aggressive harvesting, by ignoring competition (CompAgr), the same as "CompAgr" including perception error of 20% of the population death time constant (CompAgrPADE) and the same as "CompAgr"with a low barrier to entry for competition.

Important dynamics that we observe: overshoot of harvest rate for all competitive scenarios, also (but less) when the agents take competition into account.

In the case of ignoring the competition, oscillations around the equilibrium level will occur. In the case of a low barrier to entry and leave for competition, a large initial overshoot of competitors will occur (instead of overcapacity), which will later be corrected. Profits tend to 0 (Open competition).

B) Value Maximization

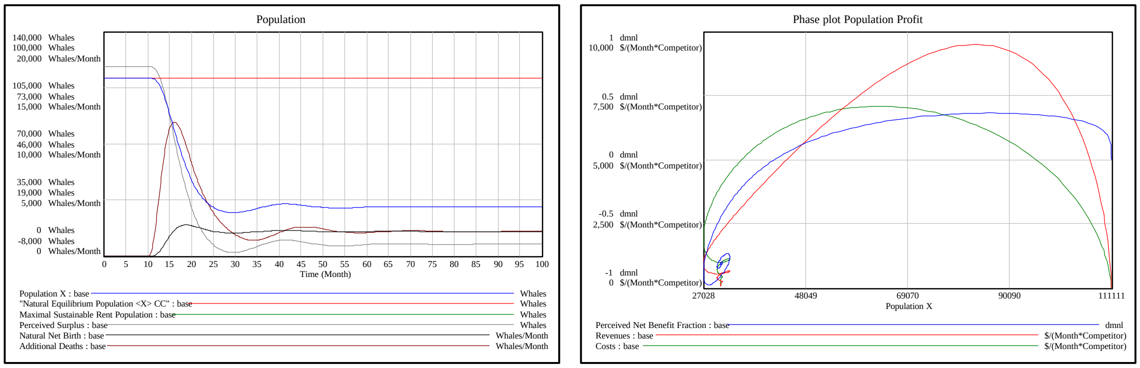


Figure B.1) Base-run: individual value maximization

Population dynamics and actual rent for individual in base run. As we can see the individual again manages to achieve a population equilibrium level, but this level (for the same numbers as in A.1) is much lower. In the phase plot on the right, population vs rent, we can observe that rent maximization is surpassed: Rent from earlier times is considered to be more important. In later times the operation is not profitable anymore.

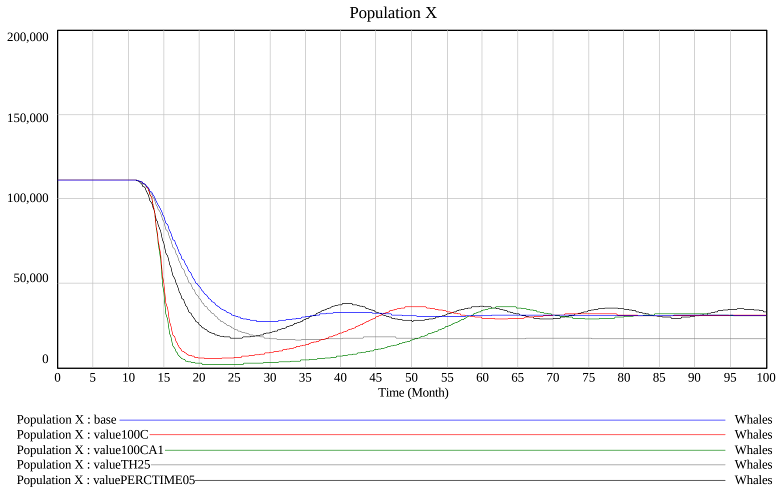


Figure B.2) value maximization - alternative scenarios

Resource population shown for different scenarios: base case, Full competition allowed (Value100C), aggressive harvesting, by ignoring competition (value100A1), shorter time horizon (valueTH25), and a faster response time to optimum than planned (valuePERCTIME05).

Important dynamics that we observe: The equilibrium level is much lower than in the case of rent maximization and overshoot is worse (as a result of value of near times is valuated higher). Especially in cases of competition this will have impact. Lower revenues as a result of this competition will again lead to the same equilibrium level. Oscillations around the equilibrium, with high amplitude.

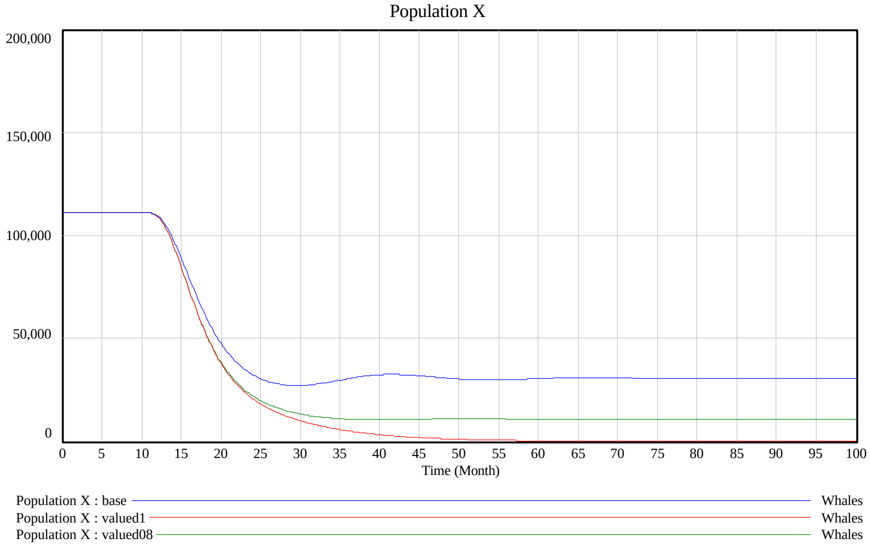
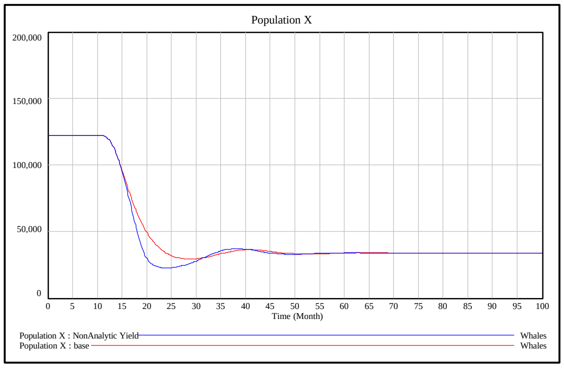
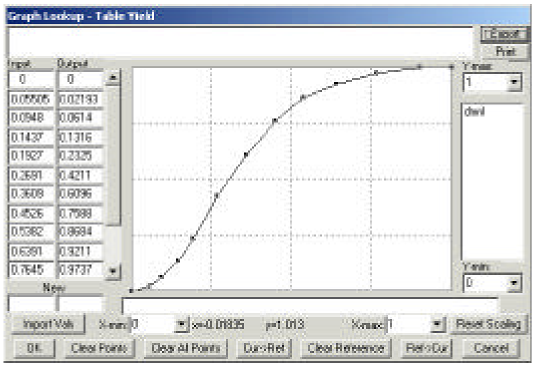


Figure B.3) value maximizing – discount rate

We observe in the graph above that also here extinction is expected when the discount rate equal to the maximum reproductive potential or MRP (valued1), unlike when it is 40% of the MRP (base), or 80% (valued08).

Finally we show dynamics in case of a more realistic yield. In this case the assumptions of the agents have not changed. See the table function as inset. The linear line is the Clark' assumption. The more realistic assumption leads to a higher overshoot and thus larger likelihood of extinction in case of lower discount rates.





Input	Output
0	0
0.05505	0.02193
0.0948	0.0614
0.1437	0.1316
0.1927	0.2325
0.2691	0.4211
0.3608	0.6096
0.4526	0.7988
0.5382	0.8684
0.6391	0.9211
0.7645	0.9737

Y-max: 1
Y-min: 0
X-min: 0
x=0.01835
y=1.013
X-max: 1

Figure B.3) value maximizing – non-analytic yield

Initial Insights

The assumption of more realistic resource dynamics, while holding on to analytical solutions for the agents' optimization problems, shows that exactly the faulty assumptions can lead to earlier depletion. Finally the explicitness of variables reveals the strength of assumptions of the agents, in case of the theoretical study. For instance the implications of different time horizons can easily be shown.

Concluding remarks

We see that the base-case model outcomes correspond to Clarks' major statements. We showed the differences in outcomes, in case of more sophisticated assumptions in behavioral terms. We do not pretend to have done a thorough analysis at all, but the initial runs and analysis show that comparability between cases provides us with richer information on the dynamics towards equilibrium levels. In general, the time delays, mis-perceptions, simplified assumptions of agents in case of economic planning, play an important role, even in such as simple and rather general case.

In this analysis approach, impacts of various simplifying assumptions for specific decision rules agents can be evaluated in relative simplified models. This can allow for increased understanding of the structure and dynamics and could for instance forego discussions on group model formulation, when both actual assumptions and real-life causal relation need to be extracted from the heads of subjects.

Discussion and projected action

In the first place, at the System Dynamics Conference, we would like to discuss usefulness of such an approach. Much more analysis is to be done to verify the proposals made here and to work towards a proper reference model.

Secondly, in support for this discussion, we will refine and extend the analysis of the Clark paper. This specific model should be improved in robustness. The result that, Clarks' profit-maximization, in combination with the dynamic physical constraints of capacity change, could imply operating under losses in the final equilibrium should be challenged. Furthermore impact of relaxation of some strong Clark assumptions should be analyzed, for instance the assumption that agents use infinite time-horizon calculations. More realistic resource dynamics should be applied (yielding non-analytical solutions for the agents optimization problem). In the realistic situation, value maximization will only occur in private and at most in limited competition environments. Impact of this sort of competition should be analyzed as well.

Thirdly we will validate and improve the reference model by exploring more quasi-empirical cases that cover problems with limited structural and behavioral deviations (focused on carrying capacity, commons, existing curtailing policies, differing decision rules and common resource pools) and in different areas (for instance forestry or agriculture).

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22. Often it is not so much attractive to stay in a certain business, but cost of decreasing capacity might be high, resulting in barriers to leave. Same way in the opposite direction: barrier to entry.
23. Clark's uses natural equilibrium population, comparable to the Carrying Capacity of the Population.

Appendix - Model Formulation

Ab Fractional Perception Error
1
Units: dmnl

Ab Timec=
60
Units: Month

Actual Harvest
Yield*Harvest attempts*Effectiveness
Units: Whales/Month

Ad Fractional Perception Error
1
Units: dmnl

Ad Timec
60
Units: Month

Additional Deaths=
External Disturbance+Actual Harvest
Units: Whales/Month

Aggressiveness=
0
Units: dmnl

Anticipated Competitors=
Aggressiveness*Min(1,max(1,PerceivedCompetition))+(1-Aggressiveness)*Perceived Competition
Units: Competitor

Basic Time Horizon=
100
Units: Month

Births=
Population X*Fractional Birth Rate
Units: Whales/Month

Business Change Time Constant=
Normal Business Change Time Constant
Units: Month

Capacity= INTEG (
+Net Capacity Increase,1)
Units: Whales/(Competitor*Month)

Capacity Holding Costs=
Capacity*Unit Capacity Cost*Fixed Costs
Units: $/Month/Competitor

Capacity Shortage=
Perceived Required Individual Rate-Capacity
Units: Whales/(Competitor*Month)

Change in Competitors=
IF THEN ELSE(Relative Attractiveness>0,
Relative Attractiveness*(Max Competitors-Competitors)/Time to Change Competition,
, Relative Attractiveness*(Competitors-Min Competitors)/Time to Change Competition)
Units: Competitor/Month

Competitors= INTEG (Change in Competitors,1)
Units: Competitor

Costs=
(Harvest attempts*Unit Harvesting Cost B/Competitors+Capacity Holding Costs)*exp(-Time*Discount Rate)
Units: $/Month/Competitor

Desired Harvest Level=
Desired Surplus Consumption+Perceived Desired Equilibrium Harvest Level
Units: Whales/Month

Desired Surplus Consumption=
Perceived Surplus/Desired Time To Reach Optimum
Units: Whales/Month

Desired Time To Reach Optimum=
Business Change Time Constant*Time Misperception
Units: Month

Desired Utilization=
IF THEN ELSE(Capacity=0, 0, max(0,Min(1,(Perceived Required Individual Rate/Perceived Yield)/Capacity)))
Units: dmnl

Discount Rate=
0.04/12
Units: 1/Month

Disturbance Duration=
5
Units: Months

Disturbance Multiplier=
0
Units: Whales/Month

Disturbance Start=
50
Units: Months

EqPop Fractional Perception Error=
1
Units: dmnl

External Disturbance=
Disturbance Multiplier*Pulse(Disturbance Start, Disturbance Duration)
Units: Whales/Month

FINAL TIME = 100
Units: Month

Financial Value Population=
1/2*(2*exp(TH*(D*T+2)/T)*PAD*T*pxc*D+2*PAD*T^2*pxc*D^2-2*PAD*T^2*pxc*D^2*exp(TH/T)+2*PAD*T*pxc*D-4*PAD*T*pxc*D*exp(TH/T)-PAb*PNX*D*T*exp(TH*(D*T+2)/T)+2*D*exp(TH*(D*T+2)/T)+3*PAb*PNX*D*T*exp(TH/T)^2-2*PAb*PNX*exp(TH*(D*T+2)/T)-exp(TH/T)*D^2*T+PAb*PNX*D^2*T^2*exp(TH/T)^2-2*exp(TH/T)*D+2*PAb*PNX*exp(TH/T)^2+D^2*T*exp(TH*(D*T+2)/T)-PAb*PNX*T^2*exp(TH/T)*D^2-2*PAb*PNX*T*exp(TH/T)*D)/(-2*D^2*T^2*exp(TH/T)+D*T-4*T*D*exp(TH/T)+D^2*T^2*exp(TH/T)^2+3*T*D*exp(TH/T)^2+D^2*T^2-2*exp(TH*(D*T+2)/T)+2*exp(TH/T)^2)/PAD
Units: Whales
Comment: this is the optimization problem that the rational agent would have to perform. In the base case it is assumed that intuitive calculations will come close to this outcome.

Fixed Costs=
0
Units: dmnl

Fractional Birth Rate=
1/Ab Timec
Units: 1/Month

Fractional Death Rate=
NPD/Ad Timec
Units: 1/Month

Harvest attempts=
Total Harvest Potential*Utilization
Units: Whales/Month

Harvest Start=
10
Units: Month

Increase Utilizatition=
(Desired Utilization-Utilization)/Time to Update Utilization
Units: dmnl/Month

Inital Population Disturbance=
0
Units: Whales

INITIAL TIME = 0
Units: Month

Max Competitors=
1
Units: Competitor

Min Competitors=
1
Units: Competitor

Natural Deaths=
Population X*Fractional Death Rate
Units: Whales/Month

"Natural Equilibrium Population <X> CC"=
120000
Units: Whales

Natural Net Birth=
Births-Natural Deaths
Units: Whales/Month

Net Capacity Increase=
Capacity Shortage/Business Change Time Constant
Units: Whales/(Competitor*Month)/Month

Normal Business Change Time Constant=
3
Units: Month

Normal Capacity=
50000
Units: Whales/(Month*Competitor)

NPD=
Population X/"Natural Equilibrium Population <X> CC"
Units: dmnl

Opportunity Costs=
0.1
Units: dmnl

PAb=
Perceived Ab
Units: 1/(Month*Whale)

PAD=
Perceived Ad
Units: 1/(Month*Whale)

Perceived Ab=
1/("Natural Equilibrium Population <X> CC"*Perceived Ab TC)
Units: 1/(Month*Whale)

Perceived Ab TC=
Ab Timec*Ab Fractional Perception Error
Units: Month

Perceived Ad=
1/("Natural Equilibrium Population <X> CC"*Perceived Ad TC)
Units: 1/(Month*Whale)

Perceived Ad TC=
Ad Timec*Ad Fractional Perception Error
Units: Month

Perceived Competition=
Competitors
Units: Competitor

Perceived Desired Equilibrium Harvest Level=
PAb*PNX*Perceived Desired Population Level-
PAD*Perceived Desired Population Level*Perceived Desired Population Level*
Perceived Desired Population Level
/PNX
Units: Whales/Month

Perceived Desired Population Level=
IF THEN ELSE(Financial Value Population>PNX, PNX, IF THEN ELSE(Financial Value Population<0, 0, Financial Value Population))
Units: Whales

Perceived Natural Eq Pop=
EqPop Fractional Perception Error*"Natural Equilibrium Population <X> CC"
Units: Whales

Perceived Net Benefit Fraction=
SMOOTH(IF THEN ELSE(Revenues=0, 0 , (Revenues-Costs)/Revenues),Smooth Time)
Units: dmnl

Perceived Population=
Population X
Units: Whales

Perceived Relative Profitability per Competitor=
(((Perceived Net Benefit Fraction-Opportunity Costs)-Opportunity Costs)/Opportunity Costs)
Units: dmnl

Perceived Required Individual Rate=
SMOOTH(max(0,(Desired Harvest Level)/Perceived Yield)*STEP(1,Harvest Start)/Anticipated Competitors, Smooth Time)
Units: Whales/Competitor/Month

Perceived Surplus=
(Perceived Population-Perceived Desired Population Level)
Units: Whales

Perceived Yield=
SMOOTH(IF THEN ELSE(Harvest attempts=0, 1 , Actual Harvest/Harvest attempts),Smooth Time)
Units: dmnl

PNX=
Perceived Natural Eq Pop
Units: Whales

Population X= INTEG (

Births-Additional Deaths-Natural Deaths, "Natural Equilibrium Population <X> CC"+Inital Population Disturbance)
Units: Whales

PXC=
Perceived Population
Units: Whales

Relative Attractiveness=
Table Profitability Attractivness(Perceived Relative Profitability per Competitor)
Units: dmnl

Revenues=
Unit Price for Stock p*Actual Harvest/Competitors*exp(-Time*Discount Rate)
Units: $/Month/Competitor

SAVEPER =
TIME STEP
Units: Month

Smooth Time=
3
Units: Month

Table Capacity Change(
[(0,0)-(25,2)],(0,0.1),(0.1,0.2),(0.2,0.4),(0.4,0.6),(0.8,0.8),(1.6,1),(3.2,1.2),(6.4,1.4),(12.8,1.6),(25.6,1.8),(512,2),(10000,2.2))
Units: dmnl

Table Profitability Attractivness(
[(-10,-1)-(10,1)],(-1000,-1),(-10,-0.96),(-8.04281,-0.877193),(-6,-0.7),(-3.63914,-0.438596),(-1.55963,-0.192982),(0.152905,-0.00877193),(2,0.2),(4.06728,0.45614),(6,0.7),(8,0.9),(10,0.96),(100,1))
Units: dmnl

TH=
Basic Time Horizon-Time*0
Units: Month

Time Misperception=
1
Units: dmnl

TIME STEP = 0.125
Units: Month

Time to Change Competition=
4
Units: Month

Time to Update Utilization=
Business Change Time Constant/2
Units: Month

Total Cost= INTEG (

Costs,   0)
Units: $/Competitor

Total Harvest Potential=
Competitors*Capacity
Units: Whales/Month

Total Profits=
Total Revenues-Total Cost
Units: $/Competitor

Total Recruitment=
Natural Net Birth-Additional Deaths
Units: Whales/Month

Total Revenues= INTEG (
Revenues,
0)
Units: $/Competitor

Unit Capacity Cost=
0.1
Units: $/(Month*(Whale/Month))

Unit Harvesting Cost B=
0.5
Units: $/(Whale)

Unit Price for Stock p=
1
Units: $/Whale

Utilization= INTEG (
Increase Utilizatition,0)
Units: dmnl

Yield=
Min(1,max(0,Population X/"Natural Equilibrium Population <X> CC"))
Units: dmnl

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