Modeling livestock systems. I. A descriptive formalism

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ABSTRACT: We attempted to categorize synthetic models of livestock production and assemble a set of descriptors for structural elements, level of resolution, operational objectives and algorithm for these models. These descriptors are suggested to be necessary and sufficient elements of the published documentation of operational model objective(s), the model algorithm and model domain of models of livestock systems. We suggest that the publication of models of livestock production require documentation of this information. Using the proposed set of descriptors, published models of livestock systems can be described systematically, allowing the evaluation of suitability to task to become more transparent and stringent. Nutrient supply level driven simulation models seem to be the model design archetype with least methodological restrictions. Their suitability to task is defined by the extent of qualitative and quantitative understanding of the relevant biology upon which they are based.

Key words: Livestock systems, systems analysis, simulation models

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Modelos de simulación de sistemas de producción animal. I. Un formalismo descriptivo

RESUMEN: Se presentan descriptores para categorizar los elementos estructurales, nivel de resolución, objectivos operacionales, y algoritmo de modelos de simulación de sistemas de producción animal. Estos descriptores son propuestos como elemntos necesarios y suficientes de una documentación de modelos de sistemas de producción animal. El uso de este formalismo descriptivo permite la descripción sistematica y la evaluccion de utilidad de modelos para objectivos definidos. El diseño de los modelos de simulación basados en la descripción bio-matematica de rendimiento animal como funcion de nutrientes disponibles parece presentar menos limitaciones metdologicas que los otros diseños. La utilidad de estos modelos es definida por el entendimiento cualitativo y cuantitativo de la biología relevante para la descripción de rendimiento animal.

Palabras clave: Sistemas de producción animal, análisis de sistema, simulación

Introduction

Nature is, when reflected upon, unity within diversity, union of the manifoldness in form and variety, quintessence of things natural and natural forces, a living whole. The most important result of research on nature therefore is: to discover unity in the manifoldness, to recognize individual discoveries made in the past, to assess these without surrendering to their number, and, mindful of the unique rôle of the human species, capture the essence of nature which is hidden under the surface of outward appearances.

Alexander von Humboldt,
Kosmos - Sketch of a Physical Description of the Universe, 1845.

Attempts at an integrative, 'systems-oriented' view of 'nature' are not new, as documented by the above citation. Research in animal production is concerned with investigation of systems on widely differing levels of aggregation. Systems have been defined in many different ways. Since the original meaning of the word 'system' implies the notion of order, it should be clear that we use this word to *conceptualize* something we can observe in the 'real' world; i.e., the system we have in mind is already a conceptual model. We apply this term to a set of interrelated things that, because of multiple interactions and change over time, is too complex to understand without the help of some descriptive formalism. The descriptive formalism is the

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model. It follows that there is no universally superior formalism or model of any one system. Accordingly, there is a need to describe existing models or modeling approaches with respect to specific objectives – what are the details of understanding that can be achieved by using a specific descriptive formalism or model. We attempt this for models of livestock systems.

Contrary to the expectations put forward in the seventies and eighties, development and use of models of livestock systems do not replace or even significantly complement experimental research in animal science nor are they a commonly accepted decision support tool for the management and planning of livestock production. However, this does not negate that models of livestock systems are useful. Since the trend towards specialization continues unabated, the need for integration of research results, and the need to translate qualitative into quantitative understanding, is becoming ever more evident. We will argue that it is the lack of progress in terms *of integrated functional understanding* in individual disciplines of animal science, e.g. nutrition, growth physiology, reproductive physiology, immunology, that hinders development and application of models. On the other hand, knowledge gaps identified by system modelers rarely find their way into research designs challenging new hypotheses. For example, modeling the effects of nutrient deficiency in extensively managed ruminants undergoing weight loss due to declining quality of pastures is currently an entirely empirical exercise. Not even an answer to the question of whether lipolysis occurs in proportion to energy deficiency or in proportion to available stored energy has been found. Such a question is fundamentally important to a systems modeler, but does not seem to be interesting to physiologists.

Properties of Livestock Systems

Animal science includes the treatment of livestock as a resource management problem. The classical "operations research" is the science of operational resource management by the use of models. Intuitively, it appears that the justification of operations research applied to livestock is redundant – operations research is a standard instrument in almost every conceivable resource management problem. However, since operations research models are not routinely applied in animal science research and management, the question needs to be asked, why do we need models of livestock systems?

The most frequently offered argument in favor of models is that systems have properties that are different from the sum of the properties of the components of the system (e.g. Whittaker, 1993). In other words, if two or more entities combine in a relationship in which matter and/or information is exchanged in some directed way, the combined entity becomes different from the sum of the individual entities. As stated above, the identification of something as a system already implies the construction of a conceptual model. This cannot be independent of specific objectives of understanding. Thus, postulating that a model is required to deal with livestock systems is somewhat a circular argument without explicitly stating the objectives of the modeling exercise. The following literature transect provides evidence for this assessment. Bywater (1990), with the broader focus on farming systems (of which livestock systems are a subset), stated: "Farm management both as an academic focus area and a professional discipline must take a systems view of the farm if it is to have any validity." Spedding (1988) stated that farms have the properties of systems. Since models represent systems, they are the analytical tool of choice when dealing with systems as a whole. Exactly this, however, is required, because, according to Spedding (1988), the ultimate goal of agricultural research is the improvement of the entire farming system, not just a component of it. Hallam et al. (1983) advocated the use of models in policy planning for the livestock sector because of the necessity to consider multiple interdependencies with other sectors of agriculture. Smith (1983) simply stated that the evaluation of the effects of different ruminant management practices requires the evaluation of the entire production system rather than isolated segments. Chudleigh and Cezar (1982) reviewed several simulation models of beef cattle production without discussing the question of why they had been created. Levine and Hohenboken (1982) summarized that the construction of a model is a way of "formalization" of current knowledge in the form of mathematical equations and their numerical solution. Cartwright (1979) stated that the classical concepts of animal breeding which define absolute merit for individual animals should be extended to the capability to define relative merit of individual animals and breeds for specific populations and environments. Wilton (1979) stressed the need to include economic considerations in animal crossbreeding programs that could only be accomplished by using models. Smith and Harrison (1978) described the construction of models as the consolidation of component knowledge obtained through the traditional analytical approach of science in order to gain understanding of complete, interactive systems. Fitzhugh and Byington (1978) categorized animal agriculture systems as complex, influenced by interacting biotic and abiotic factors so that management decisions involving only a few of these factors are unlikely to be effective. Penning de Vries (1977) discussed several ways to assign "value" to a model and the purpose of modeling in the context of the objectives of individual models rather than the rationale of the method itself. Wright et al. (1976) emphasized the value of models as an instruction and guidance tool in inter-disciplinary research. Baldwin (1976) summarized that the complex interactions within and among the environmental, digestive, physiological and metabolic elements that determine animal performance cannot be evaluated by the human mind or traditional research methods. Joandet and Cartwright (1975) suggested that the methodology developed by Forrester (1968) be used as a platform for a systematic, orderly description of beef cattle production systems in order to develop consistently optimal management policies. They stressed in particular the time-dynamic nature of beef cattle systems, characterized by the absence of steady state conditions and single optimum solutions for management problems.

Clearly, many of the justifications of models presented in the literature are circular arguments. They do not answer the question of whether there are essential research and management problems that cannot be addressed without the use of operations research models. We suggest the following formalism for the explicit consideration of objectives in a modeling exercise:

(I) Livestock systems can be described conceptually (modeled) by two different n-tuples.

Case 1:

$$\mathbf{T} = (\mathrm{i}, \mathrm{y}, \boldsymbol{g})$$

with **i** the array of input variables, **y** the array of output variables and $\boldsymbol{g}$ the set of output functions. This is the case referred to as static or single-stage.

Case 2:

$$\mathbf{Q} = (\mathrm{i}, \mathrm{y}, \mathrm{x}, \boldsymbol{f}, \boldsymbol{g})$$

with **i** the array of input variables, **y** the array of output variables, **x** the array of state variables, $\boldsymbol{f}$ a set of transfer functions which (typically) introduce time dependency into the relationship between input and output, and $\boldsymbol{g}$ the output function(s). This is the dynamic or multi-stage case.

(II) Because the **T** tri-tuple involves a possibly large number of input and output variables all of which have to be considered simultaneously in problems where multiple input-output relations are analyzed, the solution to any decision problem in livestock production systems quickly becomes nontrivial.

(III) Because (1) the transfer functions in **Q** involve multiple input variables simultaneously and (2) these functions cannot be assumed to be linear, changes in the state variables cannot be assumed to additively describe the change in the entire system between any given points in time or for any given interval in time.

In summary, it is postulated that a mathematical (i.e. operations research) model is required to research, manage and develop livestock systems because research problems involving a **T** or **Q** n-tuple are not amenable to analytical solutions. Operations research models in the broad sense are mathematical models of either static or dynamic input-output relationships.

Our discussion of a descriptive formalism for livestock system models does not address models of physiological functions on the level of quantitative biochemistry. Baldwin and Hanigan (1990) offered a concise overview in that area. See Blanc *et al.* (2001) for a review on modeling reproductive function in farm animals.

Properties of Models of Livestock Systems

Figure 1 presents an overview of model archetypes. Models in Figure 1 are synthetic models, as opposed to statistical models that are applied very frequently in animal science. Both types of models apply an interpretation framework to observed data. However, statistical models differentiate effects, i.e. reduce the dimensionality of the cause-effect relationship, without explaining functionality.

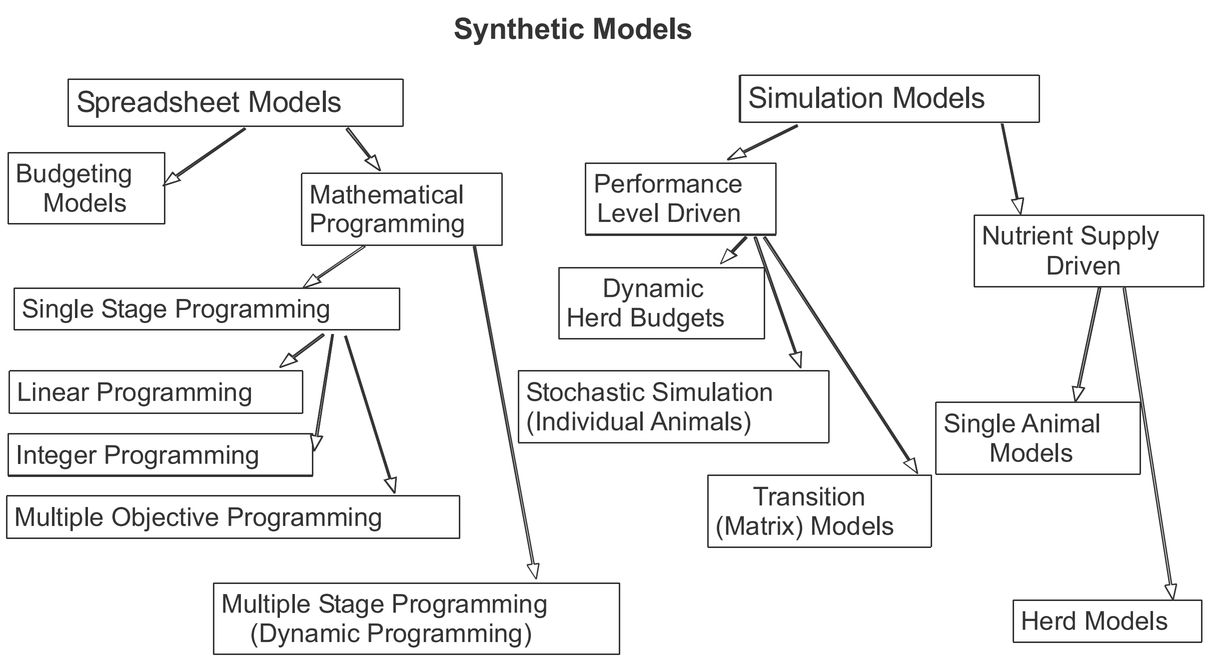

Figure 1. Types of models of livestock systems.

On the other hand, synthetic models assemble components and structure of a system into a holistic picture. While the intermediate step - reducing dimensionality by constructing a conceptual model - is the same, the decisive difference is the introduction of functionality in either a normative (optimizing models) or predictive (simulation models) approach for the synthetic models.

Models which share the **T** trituple as a common denominator are summarized as synthetic models. They are the topic of our discussion.

Model Design

Structure, boundaries, level of resolution. Synthetic models describe production systems from different viewpoints. A livestock system may be viewed as a grazing system with domestic animals as an external factor influencing plant succession (grazing management models). It may be described as a breeding system in which planned genetic selection is carried out (breeding program models). A livestock system may be looked at as part of a farm, in other words as an agricultural subsystem competing with other subsystems for resource allocation (farm management model). Animal production may be conceptualized as an animal population in management units (a herd model). Livestock systems may be aggregated into a sector of the national economy for policy planning in a macro-economic context (sector models).

The boundaries of a model are defined by a selection of elements and processes that constitute livestock production. Table 1 contains a listing of elements and processes considered to be sufficient to describe the boundaries of a livestock model. The array **x** of state variables is the logical inverse of the boundaries of the model, that is, the boundary of a conceptual model defines what is *not* included, while **x** defines what is included in the conceptual model. For static or single-stage models, state variables equal the array of output variables **y**.

Level of resolution refers to the lowest level on which these elements and processes are described. For example, a herd model that mathematically describes the physiological function "lactation" as a process operates on the level of resolution of "physiological function". Another model, that also considers lactation but does not model it as a physiological function has a level of resolution corresponding to the level on which the product of "lactation" is accounted for in the model. This may be an individual animal, category, herd or sector.

It is important to differentiate between level of resolution of the model and the level of aggregation of its results. Both terms are often used interchangeably but describe different characteristics. The level of aggregation of a model is defined by output functions ***g*** and output variables **y**; on the other hand, level of resolution is defined by the array of output variables **y** in the static case and state variables **x** and transfer functions ***f*** in the dynamic case. Output functions or output variables may or may not correspond with the level

Table 1. Structural elements of synthetic livestock system models.

Elements and processes which define boundaries of the conceptual model	Level of resolution					
	Animal	Animal Category	Herd	Breed	Mating System	Sector
Physiological function (process):						
· Growth						
· Lactation						
· Reproduction						
· Health						
Performance/Yield (element):						
· Growth						
· Lactation						
· Reproduction						
· Health						
Demographic constants						
Genetic change						
Environmental impact						
Price(s) of inputs						
Price(s) of offtake						
Demand for offtake						
Productivity/Efficiency						

of resolution of the model. For example, a model which compares economic performance of alternative livestock systems using fractions of the US $ but operates internally on a low level of resolution, i.e. consists of highly aggregated transfer and/or output functions, obviously employs output functions $\boldsymbol{g}$ inconsistent with state variables $\mathbf{x}$ and transfer functions $\boldsymbol{f}$.

Specific boundaries and level of resolution determine to a large extent the analytic capabilities of a model. Boundaries and level of resolution must be defined in accordance with the objectives which the model is intended to serve. Any attempt to relate the applicability of a model (suitability to task) to a specific research or planning problem is meaningless without the joint evaluation of stated objectives, boundaries and level of resolution. For example, nutrient supply-driven herd models have been criticized for not being capable of providing a framework for policy planning for the entire livestock sector of a national economy (Hallam et al. 1983). However, the level of resolution of these models obviously does not correspond to the level of aggregation of sector analysis; it appears that this discrepancy is the reason why they have not been used for the purpose of planning national livestock sectors rather than because of their general methodological problems, as suggested by Hallam et al (1983). Boundaries and level of resolution may not correspond with the stated objectives of the model.

For dynamic models, the specified boundaries are irrelevant for the choice of transfer and output functions. However, the level of resolution is very important for the selection of appropriate transfer and output functions. This is illustrated by reference to the model presented by Hallam (1984). This sector model considers, similar to several herd models (PRY, Baptist 1992; LPEC, Anon. 1991; Azzam 1990), reproduction, mortality and management, i.e. it shares boundaries with a quite different type of livestock model. The objective of Hallam's (1984) model is to predict the level of beef production required to meet a specified demand on the level of the entire beef production sector. For that purpose, it might be perfectly sufficient to specify, as in Hallam's model, only one survival rate for all age classes of the female breeding herd, i.e., only one highly aggregated transfer function to model population dynamics may be employed. However, if the stated objectives of this model included the optimization of herd management with a productivity index as an objective function, this transfer function would be clearly inappropriate because it does not consider major aspects of optimum herd management.

Both boundaries and level of resolution define and implement the arrays of input, state and output variables. Again, by reference to Hallam (1984), a sector model might be sufficiently detailed by combining losses and culls in one exit class. In order to model optimal management of herd assets, more state variables (e.g. culls, involuntary culls, losses) would be required.

Boundaries and level of resolution are combined in many different ways in published livestock system models. Therefore, Table 1 will serve as the basis for the discussion of model objectives, algorithms and planning horizons as additional methodological criteria of models of livestock production systems.

Table 1 has several entries for the structural elements of a livestock model pertaining to performance traits. Depending on the algorithm of the model, entries in these rows define essential differences between model designs, as will be explained below.

Objectives and structure. The overall objective of animal science is to increase the efficiency or the productivity of livestock production systems. Recently, the goal of sustainability has been introduced: a system which is more productive or efficient in the short term than the system it replaces may not necessarily retain this comparative advantage over extended periods of time because it may degrade its natural resource base. Thus, the attribute "sustainable" requires the assessment of efficiency or productivity on a more extended time scale than commonly used for productivity analyses.

It is surprising how frequently the term "productivity" is used inappropriately (see Baptist (1991) for an extensive discussion). A rigorous definition of productivity appears to be required: Productivity is the ratio of output to input. Hence, productivity is not equal to physical production.

The strategic goal "improvement of productivity and sustainability" may not be identical with the tactical (operational) objectives of a model-based analysis of livestock systems - often models are made to improve understanding of and plan experimental work on real systems. However, models may be chosen based on a purposeful selection of model design, or based on available models. This distinction often appears to be less than clear-cut.

The determinants of livestock productivity:

- Reproduction
- Mortality
- Yield
- Time

are defined, according to the postulates about the rationale of modeling livestock systems, by the **Q** quintuple. The analyst may choose to *not* consider time as a determinant. In that case, an operations research model based on the **T** n-tuple would be the tool of choice. This reduction in scope implies analytical limitations that need to be discussed in the context of the stated objectives of published models and in the context of methodological problems of model designs. At this point, it suffices to state that the first distinction between synthetic model designs is defined according to whether they are based on either the **T** or the **Q** n-tuple. This principal design difference is an important element in the definition of suitability to task.

Improvement of productivity and sustainability of livestock systems involves understanding of function, prediction of reaction and evaluation of reaction over time of these systems, by implementing a suitable model based on the **Q** n-tuple. If the analyst determines that the use of a static model is adequate according to the objectives of the study, an evaluation of the principal constraint of this approach (the condition of time constancy of input variables and response) is nevertheless required. This evaluation seems to be generally absent from the published literature.

Because the synopsis and synthesis of detailed subject knowledge in the subdisciplines of animal science is becoming increasingly difficult, the role of models as an aid to understanding complex processes in animal production is frequently stressed. The early use of synthetic models of livestock systems as repositories for detailed knowledge about elements and processes determining the subject of livestock research - offtake of animal products - led Penning de Vries (1977) to the classification of synthetic models into scientific, predictive and instructive designs. Many other labels have been created for ordering synthetic models according to their operational objectives. Brockington (1979) divided simulation models into black-box and mechanistic models; Whitson and Kay (1978) differentiated between predictive and explanatory optimizing models; proceedings of an EEC seminar (Korver and van Arendonk 1988) listed animal models, herd models and population sector models. We hold that a classification scheme emphasizing operational objectives is the most useful for the purpose of evaluation of suitability to task.

A summary of operational objectives of different synthetic model designs follows:

- ***Spreadsheet Models*** evaluate livestock systems with the objective to establish cost-benefit relations; the set of output functions always includes constraints,
  - *Spreadsheet Models: Budgeting* evaluate the cost-benefit structure of livestock production without introducing a norm: optimization is not implicit; time is not considered.
  - *Spreadsheet Models: Mathematical Programming* evaluate livestock with the objective to "optimize" the input-output structure (as a superset of cost-benefit relations) of a livestock system according to externally supplied objective function(s) and constraint(s); define livestock production entirely as a resource management problem.
  - *Spreadsheet Models: Mathematical programming: Single Stage Programming* livestock production is modeled as a single stage resource management problem. Time is not considered to affect the optimal solution.
  - *Spreadsheet Models: Mathematical Programming: Dynamic or multi-stage programming* resource management in livestock production is modeled as a multi-stage but single component resource management problem. For example, replacement strategies for female breeder herds are evaluated for individual animals independently of concurrently managed animals of the same category (components); there is a technical restriction (computing time, model complexity) on the level of detail with which the resource may be modeled.
- ***Simulation Models*** solve numerically a set of mathematical equations for the evaluation of state variables; the set of output functions may or may not include constraints; there is no restriction on the number of stages or components considered.
  - *Simulation Models: Animal performance driven* evaluate the offtake of livestock systems by supplying, among other input variables, data for actual animal performance.
  - *Simulation Models: Nutrient Supply Driven* evaluate the offtake of livestock production or processes determining livestock production as a function of nutrient supply to animals.

Thus, synthetic model are constructed for *understanding* (a platform for hypothesis testing), *predicting* (a decision aid), *comparing* (a surrogate for field experiments), and *optimizing* (resource allocation and management) the properties of livestock production systems.

These operational objectives of synthetic models must now be integrated with boundaries and level of resolution to extend the set of methodological characteristics required for a comparative discussion. Boundaries and level of resolution define the presence or absence and formal representation of the four determinants of livestock productivity. Thus, Table 1 is extended with the following entries (Table 2) to provide for a concise definition of operational objectives of models in the context of their structure.

Of course it is debatable whether "assume" should be considered an operational objective; however, for a model assuming one of the left-hand entries of Table 1, it is rather safe to state that for practical purposes, the use of an assumption constitutes an operational goal.

The operational objectives of the model presented by Hallam (1984) are summarized as an example (Table 3).

This concise overview of operational model objectives provides a convenient basis for model comparison. It will now be extended by information about the way in which reproduction, mortality, yield and time (the determinants of livestock productivity) are connected. Algorithm and planning horizon of the model determine the design of these connections.

Algorithm and Operational Objectives

In modeling livestock systems, few standards are agreed upon. Nowhere is this more obvious than in the discussion of the relationship between the stated operational objectives and the algorithm employed in a model. In this section we refer to algorithms exclusively within model design type. Different designs are frequently applied to the same research and management problems. In this context, the discussion of algorithms receives a more fundamental notion. The first and most important classification of algorithms was already presented: we differentiate between single-stage or static and multi-stage or dynamic model designs.

Discussions of the characteristics of algorithms employed in single stage mathematical programming models are plentiful and can be found in standard textbooks (e.g. Taha 1987; Winston 1991). For the single stage case, we need two descriptors for *model algorithm*:

- mode of specification of input variables (deterministic or stochastic);
- optimization algorithm.

Since budgeting and single-stage programming models (LP, integer programming, goal programming and variations) do not consider time, they may be considered point models.

For multi-stage models, four descriptors of *model algorithm* are necessary:

- mode of specification of input variables (deterministic or stochastic);
- mode of formulation of transfer functions (deterministic or stochastic);
- mode of model formulation: single or multi-component;
- optimization method.

A single component formulation considers only one instance of the resource which is modeled. For example, a herd replacement model which models only one female breeder and then integrates the result into a higher aggregation level (e.g., herd), is a single component formulation. A multi-component formulation takes relationships between instances of the same resource unit into account. For example, a multi-component herd model acknowledges that management decisions on a certain animal are usually not independent of other animals in the herd. That is, the attributes relevant for management decisions of all animals in the herd are considered for the decision on individual animals.

Table 2. Operational model objectives.

Operational Objective
Understand
Predict
Compare
Optimize
Assume

The choice of a particular algorithm for the implementation of a conceptual model should be in accordance with the stated objectives of the model. The formulation of prediction (simulation) models is very flexible: They may be implemented as a process model or as an event-driven model; time may be treated in discrete steps or continuously. Input variables and/or transfer functions may be stochastic or deterministic. At this point, it does not appear to be justified to suggest without ambiguity a specific algorithm as a requirement to meet operational model objectives. However, methodological problems of simulation models are strongly connected to their algorithms. In general, predictive models are much more flexible with regard to the choice of an algo-

Table 3. An example for the description of operational model objectives (Hallam 1984).

Elements and processes which define boundaries of the conceptual model	Level of resolution					
	Animal	Animal Category	Herd	Breed	Mating System	Sector
Physiological function (process):						
· Growth						
· Lactation						
· Reproduction						
· Health						
Performance/Yield (element):			predict			
· Growth		assume	predict			
· Lactation		assume	predict			
· Reproduction		assume	predict			
· Health			predict			
Demographic constants		assume	predict			
Genetic change						
Environmental impact						
Price(s) of inputs						
Price(s) of offtake						
Demand for offtake						assume
Productivity/Efficiency						predict

rithm than normative models. For example, for multi-stage explicit optimizing models, i.e. dynamic programming (DP) models, the choice of algorithm is determined almost exclusively by the level of resolution on which the system is described. The rationale of DP is the decomposition of an optimization problem into separate stages. A necessary criterion, therefore, for a problem to be described as a DP model is that the objective function can be decomposed into separate stages ("is separable"). A stage in a DP model of livestock systems is generally a unit of time, often conveniently set congruent with a certain management cycle. For the principle of optimality (Bellman 1957) to hold, the management problem has to be defined in a way that the state of the system at any stage depends only on the situation of the preceding stage. This is the so-called Markov property. Most DP models of livestock systems are based on Markov processes, i.e. a stochastic formulation of transitions between stages. Decision process models of the replacement problem in the female breeding herd appear to be the most frequent application of DP in animal science (for a broad discussion of DP applications see Kennedy (1986)).

It is important to point out a difference in meaning of the term 'state variable' between simulation and DP models: a state variable in a simulation model contains the current (numerical) value of e.g., a production trait such as weight or lactation yield. However, in a DP model a state variable denotes, in general terms, the set of constraints that bind the stages together (Taha 1986), or in other words, a state describes the information required to make an optimal decision at any stage. In the specific case of replacement DP models, state variables are the set of attributes which jointly describe the state of the resource (e.g., a cow) at stage t. Transitions between these states are, in the case of most replacement models, governed by optimum management decisions and probabilities (an alternative formulation would employ differential equations). Thus, states are instances of discrete attributes. These attributes may include age class, genetic group, lactation number, lactation stage and so forth. More realistic DP models of the replacement problem arrive at up to 180,000 possible states resulting from a combination of a relatively small number of state variables (Kristensen 1992). At each stage, possible states must be specified for the next stage and transitions determined. The states of all components must be evaluated simultaneously. It is, therefore, easily conceivable that the degree of realism of the description of the resource, that is the number of attributes which may be evaluated concurrently, limits the modeler's choice of an algorithm. This limitation even extends into the choice of a feasible planning horizon, as will be discussed below. Most importantly, it makes it impossible to treat the replacement problem in livestock as a multi-component, i.e. herd problem. In other words, in order to be solved with today's known computational methods, dynamic programming models can only consider a single animal, as discussed by Kristensen (1992). To clarify this point further, practically all published DP models of replacement management assume decisions about individual cows in the herd to be independent of all other cows in that herd and of available replacement heifers. This assumption does not appear to be very realistic. The specific model design of DP models explains the importance of the algorithm descriptor "mode of model formulation", i.e. whether the resource management problem is formulated either as a single-component or multi-component model. In the case of models which consider livestock production as a subsystem of a farm, the multi-component formulation would pertain to the allocation of available inputs.

This example briefly illustrates that methodological limitations of a specific model design may not become readily apparent without considering available alternatives. Again, model users must be cognizant of their objectives and carefully weigh them when choosing a model design.

We may summarize that predictive or simulation models enjoy great flexibility in choice of algorithms. This does not necessarily mean that methodological problems of simulation models are independent of their algorithms.

On the other hand, normative multi-stage models (dynamic programming models) always have to resolve a conflict between model boundaries, level of resolution, objectives and feasible algorithm.

We add the following symbols for the description of synthetic models based on Table 1.

- D: variable specification: deterministic mode
- S: variable specification: stochastic mode
- I: input
- O: output
- SC: single component model
- MC: multi-component model

For example, the combination I-D refers to the deterministic formulation of a certain element as input. O-S would denote the application of a stochastic output or transfer function to the corresponding element by the model. O-D or O-S in rows corresponding to *Physiological function* for the column *Animal* would correspond to models which employ transfer functions to describe the corresponding traits, i.e. attempt to mathematically model the physiological processes involved. If there are only entries in the *Performance/Yield* row, the model would not consider transfer and output functions determining the level of performance traits on the level of *Animal*. Rather, an entry in this row in columns other than *Animal* would indicate the presence of output and transfer functions aggregating input provided on the level of *Animal* into higher-level output variables.

Generally, the descriptors of an algorithm as defined above, are not confined to one specific synthetic model design. The model presented by Kristensen (1992) serves as an example of how to integrate descriptors of algorithms with the methodological characteristics developed in the preceding sections. This model was chosen because it is particularly difficult to classify since it is a design that combines dynamic programming and stochastic simulation. Even though Table 4 is not a comprehensive representation of all methodo-

Table 4. Methodological properties of the model presented by Kristensen (1992).

Elements and processes which define boundaries of the conceptual model	Level of resolution					
	Animal	Animal Category	Herd	Breed	Mating System	Sector
Physiological function (process):						
· Growth						
· Lactation	assume; I-S					
· Reproduction	assume; I-S					
· Health						
Performance/Yield (element):						
· Growth						
· Lactation						
· Reproduction						
· Health						
Demographic constants		assume; *I-S*				
Genetic change	assume; I-S					
Environmental impact						
Price(s) of inputs						
Price(s) of offtake			assume; *I-S*			
Demand for offtake						
Productivity/Efficiency	*M-C*		predict; *O-S*			

logical characteristics of a simulation model, it assembles the major attributes required for comparative discussion.

Differences between models assuming animal performance and aggregating results on a system level and those employing transfer and output functions on the level of *Animal* are best illustrated by presenting a nutrient supply-driven simulation model.

The models presented in Tables 4 and 5 address two closely related problems, the production of replacement heifers and optimization of the replacement strategy in dairy herds. Yet, as evidenced by their methodological properties, they employ fundamentally different designs. These differences are important for suitability to task. because the question of whether physiological functions on the level of ANIMAL are either assumed as inputs or predicted from mechanistic equations can make a decisive difference. For example, Kristensen's (1992) approach cannot accommodate differences in feeding management which affect the dairy quality of first calf heifers. Undoubtedly, if such differences are significant, as Sørensen's model calculations indicate, they should be considered in a multi-component optimization model for reproduction which depends upon on a measure of herd quality.

Planning Horizon and Algorithm

The discussion of planning horizon for synthetic models is presented separately for predictive and normative models.

For all normative models, the choice of planning horizon is dependent on the choice of algorithm; however, only for few predictive models is this the case.

Single-stage normative models treat planning horizon as an implicit given. For these models, planning horizon equals the length of time for which no systematic change in input variables and constraints occurs.

For multi-stage normative models (dynamic programming), choice of planning horizon cannot be separated from the formulation of the model. As an example, according to van Arendonk (1984), the optimum policy in a cow replacement model (as discussed above) is a function of the time over which the model is evaluated. The point in time at which the optimum policy becomes invariant, i.e. does not change with additional stages evaluated in the recursive equation, might be chosen as the end of the planning horizon. This means in essence that the planning horizon (which could be argued to be a part of the research problem) becomes a variable depending on properties of the model. It

Table 5. Methodological properties of the model presented by Sørensen (1989).

Elements and processes which define boundaries of the conceptual model	Level of resolution					
	Animal	Animal Category	Herd	Breed	Mating System	Sector
Physiological function (process):						
· Growth	predict; O-S	predict; O-S				
· Lactation	predict; O-S	predict; O-S				
· Reproduction	assume; I-S	predict; O-S				
· Health	assume; I-S	predict; O-S				
Performance/Yield (element):						
· Growth						
· Lactation						
· Reproduction						
· Health						
Demographic constants						
Genetic change						
Environmental impact						
Price(s) of inputs		assume I-D				
Price(s) of offtake		assume I-D				
Demand for offtake						
Productivity/Efficiency	*M-C*		predict; *O-S*			

is most interesting to note that different DP formulations of the cow replacement problem lead to different optimum solutions and to different time periods (here set equal to planning horizon) required to reach solution constancy (see van Arendonk 1984). This characteristic of DP models is fundamentally different from the general perception of mathematical programming being capable of identifying unequivocal optima.

On the other hand, if an infinite planning horizon is chosen, the management policy that is to be optimized has to be assumed equal for each stage (van Arendonk 1984, Kristensen 1988). This restriction may be expressed alternatively as the requirement for the returns and transformations modeled to be constant over time (stationary) (Kennedy 1986). This means that no systematic changes in, e.g. prices, product relationships, yields and so forth may be considered in the model except in additional state variables. Since the computation load of DP models grows exponentially with the number of state variables, any attempt to relax the stationarity requirement for an infinite planning horizon compromises the feasibility of implementation of the model. A potential aid but not a principal solution is the use of hierarchic Markov processes in model formulation (Kristensen 1987). Hierarchic Markov process models produce approximate solutions, and in the case of Kristensen (1992), the important entity "herd quality" is derived by a simulation model and not an integral part of the optimization process. However, any compromise between choice of planning horizon and model formulation depends ultimately on implementation and computation resources.

The question of planning horizon for predictive models has not been the subject of thorough discussion in the literature.

For herd models, Upton (1989) and Baptist (1991) argued that the comparison of alternative management systems and breeds should abstract from initial conditions and time taken for the simulated system to stabilize after induced changes. This could be achieved by assuming populations of infinite size with time-invariant structure. Herd or population models based on Markovian transition matrices (Azzam et. al, 1990) or actuarial methods (i.e. using life and fecundity tables, Baptist, 1992) require the assumption of a stationary population; i.e. they have to assume an infinite planning horizon.

Indeed, herd models serve as an excellent anchor for a discussion of the topic of planning horizon. Is it possible or desirable to separate the effects of herd size and herd composition from the effects of systematic factors of influence such as breed and management regime that are intended to be compared and ranked? Most predictive herd models specify arbitrary initial herd sizes and compositions and then simulate these herds under constant herd management regimes to achieve what is often labeled the "steady state" of the herd. At the steady state, simulated herds are supposed to be free from the effects of initial numbers, herd composition and herd size, and size and composition are assumed to remain approximately constant after this equilibrium point has been reached. However, only one reference (Baptist, 1987) was found which actually analyzed this alleged property. A steady state of a herd may be considered to be equivalent to an infinite planning horizon if different policies are evaluated for similar herds in the steady state. However, while alternative policies may all lead to steady state conditions, these steady states may be quantitatively and qualitatively quite different.

Brockington (1992) alluded to the problem that confronts producers who decide to adopt a new management policy or to change the genetic performance potential of their livestock. It appears to be precisely the time between implementation of change and realization of expected improvements that is a critical element in the ranking of policy alternatives. Upton's (1989) arguments in favor of the stationary state or infinite planning horizon appear to be inconsistent with his contention that many livestock production systems are highly variable. For highly variable production systems due to uncontrollable external factors such as prices and climate, it is quite possibly the reaction norm of the system over limited time intervals that is the topic of interest. If that is the case, the question of planning horizon (in the sense of generating comparable simulation scenarios) becomes irrelevant; what matters is the length of the time period over which reasonable predictions can be made for uncontrollable external factors.

Variability of major determinants of productivity appears to be the most important consideration in the choice of a planning horizon. In other words, not only the objectives of the study (understanding, prediction, comparison or optimization) determine suitability to task of different model designs, but also intrinsic properties of the modeled system. That is, the analysts are not entirely free in their choice of appropriate model designs. This predetermination frequently has not been considered in the past when resource management problems in livestock production where tackled by synthetic models. The important conclusion is drawn that the choice of appropriate planning horizon across which a system is modeled is a function of the operational objectives of the model. However, there is a close relationship between certain properties of livestock systems and attainable and/or useful operational goals of a simulation exercise. For some model designs, there is little or no choice of planning horizon. The majority of predictive models can be run across any type of planning horizon. We strongly suggest using the criterion of planning horizon in defining suitability to task of specific models.

Table 6. Operational validation and model application objectives.

Model objective	Validation	Method
Test hypotheses	not required	
Plan field research	desirable	subjective or objective
Recommend policy	required	objective & reproducible

Model Domain

Model domain, according to the Technical Committee on Model Credibility of the Society of Computer Simulation (SCS Technical Committees, 1979) is defined for simulation models in two ways:

1. Domain of intended application (of conceptual model): Prescribed conditions for which the conceptual is intended to match reality.
2. Domain of applicability (of the computerized, i.e. coded conceptual model): Prescribed conditions for which the computerized model has been tested, compared against reality to the extent possible, and judged suitable for use (by model validation). Validation, as defined by SCS (op.cit), is the substantiation that a computerized model within the domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model. Range of accuracy is understood as the demonstrated agreement between the computerized model and reality within a stipulated domain of applicability.

Thus, the discussion of model domain introduces the arguably most controversial issue in modeling, the validation problem.

This problem does not exist, de facto, for spreadsheet models - at least not in the literature. No model of this subgroup was found to discuss the validation problem. However, it appears to be relevant and legitimate to ask the question whether a specific selection of input and/or state variables and their formulation is consistent with a) the system modeled, b) with the objectives to be accomplished by the use of the model. A discussion of this question for spreadsheet models is beyond the scope of this paper. Instead, we concentrate on validation of predictive models. However, we postulate the absence of any principal difference between spreadsheet and simulation models with respect to the requirement for validation.

Sørensen (1990) reviewed validation of simulation models of livestock herds. The author concluded from a brief survey of published herd models that validation is often not carried out satisfactorily for these models. It appears to be a particular nuisance that in our normal language, validation is used interchangeably with verification (Rykiel (1996) offers a concise overview of the semantics involved.) The discussion of whether validation is possible at all has two dimensions. First, it might be argued that validation in the sense of verification is impossible because synthetic models share critical properties with scientific hypotheses. According to the dominating positivistic view of science, scientific hypotheses can only be refuted, not proven. It could further be argued that any observable state of nature is logically compatible with a probabilistic hypothesis about it (livestock models, even without stochastic elements, are probabilistic hypotheses), and therefore, models cannot be verified. Second, the question of the operational feasibility of validation arises. Sørensen (1990) concluded that the validation of “complete livestock production system models” is almost impossible because of the scarcity and unreliability of observational data against which a comparison must be made. The comparison of aggregated herd model data with observational data is termed “operational validation” of the model by Sørensen (1990). We do not agree with the point of view that operational validation is next to impossible for herd models in general. If the herd model to be validated does not provide for the examination of intermediate biological processes on the level of aggregation commonly observable in livestock production (e.g. growth data, lactation data, reproductive performance data), but requires these data as input (performance level driven models), the comparison of aggregated model data with aggregated production data is required. This immediately creates the problem of, e.g., discrepancies between management cycles simulated in the model and those possibly applied in the field (but not necessarily transparent to the analyst). Producers might have pursued other objectives than those considered in the model; market perturbations might have influenced observational data without these perturbations being captured in the model. In other words, the validation of livestock models becomes increasingly difficult with the level of aggregation of the data which are compared because the amount of unexplained variation (sources of variation not considered in the model) increases. Thus, if the validation of a model involves the consideration of the entire highly aggregated production system, the effort involved to provide for enough observations against which to compare increases dramatically.

On the other hand, the possibility of examination of intermediate biological processes in the simulation model almost automatically provides for increased opportunities for comparison with observational data. Of course, the question arises, if only intermediate results of a herd model are intended to be validated, does this ensure validity of the entire model? This question can be answered positively if the aggregation is a mere, albeit sophisticated, accounting procedure as in the case of performance potential driven herd models. If additional transfer functions are employed, the operational validation with aggregated observational data is inescapable. However, this seems to be an issue only models that incorporate economic elements into the simulation of biological processes.

The question of whether validation is a requirement depends on the objectives served by the model. The following summary provides a guideline:

In summary, the validation problem in the practical application of a livestock simulation model must be solved according to the operational objectives of the model. It is difficult to conceive that decision makers in livestock production would base their actions on model results which cannot be or have not been compared with production data. Thus, the definition of the domain of a model in the sense outlined above is a desirable component of model documentation. This argument is in line with the recommendations of Shannon (1975), Velayas and Levary (1987), Law and Kelton (1991), Oreskes et al. (1994), Rykiel (1996) and Mitchell (1997), all of whom support the notion of validation of a model as being a matter of degree. Where there are no universal and absolute standards for validation, the relation of stated objectives to stated performance of the model becomes a central element of model documentation, and therefore, the description of model domain and operational objectives is critical.

We summarize the discussion of model domain as follows:

The description of the domain of a model requires the following elements:

- model objectives;
- structural elements and processes (boundaries);
- level of resolution;
- validation as a function of objectives.

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