Decision-making tools: stochastic simulation model accounting for the impacts of biological variation on success of bovine embryo transfer programs[1]

Dustin G. Aherin,[†,2] Jennifer M. Bormann,[†] Jessica L. Heier Stamm,[‡] Michael D. MacNeil,[†,§,‖] and Robert L. Weaber[†,2,3]

[†]Department of Animal Sciences and Industry, Kansas State University, Manhattan, KS 66506; [‡]Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506; [§]Delta G, Miles City, MT 59301; and [‖]Department of Animal, Wildlife and Grassland Sciences, University Free State, Bloemfontein, South Africa

ABSTRACT: The objective of the project was to create an economic risk analysis tool for user-defined embryo transfer (**ET**) programs as an aid in decision-making. Distributions defining the biological uncertainty for many reproductive outcomes are estimated through extensive literature review and limited industry sources. Applying the Latin hypercube variation of Monte Carlo simulation, a sample value from the descriptive distribution associated with each stochastic variable is included in each iteration of the simulation. Through large numbers of iterations with dynamic combinations of variable values, the process culminates in a distribution of possible values for the net present value, annuity equivalent net present value, and return on investment associated with the modeled embryo production scenario. Two options for embryo production, multiple ovulation embryo transfer (**MOET**) and in vitro embryo production (IVP) from aspirated oocytes, are modeled. Within both MOET and IVP, the use of unsorted or sex-sorted semen is considered, as well as the exception or inclusion of follicular synchronization and/or stimulation before ovum pick-up in IVP procedures. Pretransfer embryo selection through embryo biopsy can also be accounted for when considering in vivo derived embryos. Ample opportunity exists for the commercial application of in-depth, alternative ET scenario assessment afforded through stochastic simulation methodology that the ET industry has not yet fully exploited.

Key words: beef cattle, economics, embryo transfer, investment analysis, risk, stochastic modeling

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[1]The opportunity given to me by Michael Rea, formerly of Stevenson Sputnik and currently ORIgen Embryo Technologies, and Darrell Stevenson, Stevenson Angus, and Stevenson Sputnik, to work alongside an elite team on a massive ET project not only helped inspire this specific project but also opened my mind to the immense possibilities that can be created by challenging the norm. Continual conversations with Michael and Darrell, as well as Matt Barten, Embruon, helped spur ideas and create the vision of what this model has become and what it could be.

[2]Present address: Department of Animal Sciences and Industry, Kansas State University, 227 Weber Hall, Manhattan, KS 66506

[3]Corresponding author: bweaber@ksu.edu

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INTRODUCTION

Dynamic environments, varying production practices, and biological uncertainty associated with bovine reproduction make informed, strategic decision-making regarding implementation of bovine reproductive technology a great challenge for producers. Profitability of an embryo transfer (**ET**) program depends on marketability of the end products (embryos, pregnant recipients, progeny, etc.) and expenses required to produce them.

A primary contributor to the success of any ET program is the ability to generate transferable embryos. Referring to multiple ovulation embryo transfer (**MOET**), Hasler (2003) states, "I believe that the current success level of superovulation represents a significant obstacle to the future growth of the ET industry. As long as mean embryo production remains at less than 6, with a range of (0 to >60), with 20% of donors producing zero embryos, superovulation will remain an expensive, inefficient procedure." Bo and Mapletoft (2014) share a similar view, "…Thus, a high degree of unpredictability in super-ovulatory response still exists more than 35 years later, creating problems which affect the efficiency and profitability of commercial embryo transfer." Success rate of in vitro production (**IVP**) of embryos varies due to number of oocytes collected per ovum pick-up (**OPU**) session, in vitro fertilization (**IVF**) rate, and the rate at which embryos become blastocysts. Although approximately 80% of naturally occurring, single ovulating oocytes develop into embryos following IVF and approximately 60% of oocytes following superovulation develop into embryos, the rate of embryo development for OPU–IVP embryos tends to range from 10% to 40%, depending on oocyte and semen quality (Merton et al., 2003; Pontes et al., 2010; Morotti et al., 2014). Everett et al. (1978) demonstrated significant variability in semen quantity and quality. Semen quality differences, as evidenced by variation in blastocyst rate, exist (Ramos et al., 2010; Antonio de Carvalho Fernandez et al., 2014; Barcelo-Fimbres et al., 2015) and gender-specific sorting compromised it (Palma et al., 2008; Morotti et al., 2014).

Cumulatively, overall embryo grades and fresh or frozen embryos, the pregnancy rate of IVP embryos was significantly lower than in vivo derived (**IVD**) embryos. (Farin and Farin, 1995; Hasler et al., 1995; Pontes et al., 2009).Chagas e Silva et al. (2002) and van Wagtendonk-de Leeuw et al. (2000) reported that pregnancy rates were similar between IVP and IVD embryos, highlighting the variability of outcomes.

Recipient management and synchronization cost comprise a considerable expense. Thus, the percentage of recipients deemed eligible to receive an embryo following estrous synchronization affects the economic viability of an ET program. Many different protocols exist for recipient estrous synchronization, and the degree of synchrony achieved is variable (Looney et al., 2006).

Following ET, recipients may be exposed to a natural service sire, with considerable variability in resulting pregnancy rates (Bellows et al., 1979; Lamb et al., 2008) postbreeding season.

Early embryonic mortality may account for as much as 57% of the lost pregnancies (Inskeep and Dailey, 2005). Nevertheless, fetal survival to term does not guarantee a marketable product. Bellows et al. (1979) reported that of 10,300 calving cows that had conceived via natural service, 8% of calves died in the perinatal period, and an additional 2.9% died before weaning. King et al. (1985) found that neonatal calf loss, birth weight, and calving assistance were similar between IVD ET calves and non-IVD calves. Perinatal mortality of calves produced by MOET was similar to calves produced by AI, although calving difficulty and gestation length were significantly increased (van Wagtendonk-de Leeuw et al., 2000).

The first indication of abnormality from IVP embryos was exceptionally large offspring at birth (Farin et al., 2015). This phenomenon, now called abnormal offspring syndrome (**AOS**), has caused concern regarding survival of IVP embryos from time of transfer through the neonatal period. Increased birth weight, gestation length, and calving difficulty of IVP calves relative to AI and MOET have been observed (van Wagtendonk-de Leeuw et al., 2000). Furthermore, van Wagtendonk-de Leeuw et al. (2000) and Kruip and den Daas (1997) reported that IVP calves had greater perinatal mortality than AI or MOET. Conversely, origin of embryo and birth weight had no impact on subsequent growth (Wilson et al., 1995; McEvoy et al., 1998). Little to no current literature exists on industry prevalence of AOS (Hasler, 2014).

The multitude of stochastic factors, decision points, and potential interactions among them motivated the development of a simulation model for their joint consideration in assessing the economic feasibility of alternative ET programs.

MATERIALS AND METHODS

Goals and Approach

A circumstantial, stochastic prediction model was created utilizing @Risk 7.5 (Palisade

Corporation, Ithaca, NY) to assess economic viability of various ET programs as an aid in the decision-making process. User-defined, deterministic parameters are accompanied by stochastic variables of economic importance to generate a flexible model. Distributions defining biological uncertainty for a multitude of reproductive outcomes are estimated through extensive literature review and limited industry sources. Distributions can be altered based on user expectations. Deterministic override options are also available within the model interface. Latin hypercube sampling (**LHS**) is applied to the Monte Carlo simulation model. The evaluative process culminates in net present value (**NPV**), annuity equivalent net present value (**ANPV**), and return on investment (**ROI**) distributions.

Model Outline

The 10 various ET protocols currently included in the default model are outlined below and are permutations of embryo collection method, sexed-semen selection, and embryo biopsy options. Figure 1 depicts the structure of the underlying ET production system model that performs simultaneous evaluation of the different protocols subject to a user-defined scenario. Potential alternatives in ownership and marketing strategies also undergo simultaneous evaluation within the model.

1. MOET: unsorted semen
2. MOET: sex-sorted semen
3. MOET: frozen biopsied embryos
4. MOET: frozen non-biopsied embryos
5. IVP: no ovarian stimulation (NS), random OPU interval, unsorted semen
6. IVP: no ovarian stimulation (NS), 3 to 4 d or 14 d OPU interval, unsorted semen
7. IVP: follicular synchronization and ovarian stimulation (SS), unsorted semen
8. IVP: NS, random OPU interval, sex-sorted semen
9. IVP: NS, 3 to 4 d or 14 d OPU interval, sex-sorted semen
10. IVP: SS, sex-sorted semen

The economically relevant probability distributions described in the "Distributions of Biological Uncertainties" section illustrate the potential range of possibilities when transitioning from one stage of production to another. The results of each stage of production serve as inputs for the subsequent transition to the next stage of production.

Embryo Production Model and Descriptions

MOET unsorted semen embryo production. For Protocol 1, let n be the user-defined, deterministic variable for the number of donors in the ET program. The number of donors collected following each round of superovulation is calculated using a binomial distribution with n number of donors in the ET program and probability, P, of a donor showing signs of estrus and being subsequently inseminated and flushed. Probability, P, equals one minus the probability of donors not showing estrus after superovulation; this is sampled stochastically per LHS from the probability distribution of the mean rate of donors not showing signs of estrus following superovulation. The number of donor superovulations is entered as a user-defined deterministic variable. The number of embryos collected per flush is sampled stochastically per LHS using the negative binomial distribution (Woolliams et al., 1995) describing the number of embryos retrieved per collection.

A user-defined, deterministic variable with a minimum of 30 d determines the time interval between flushes. To maintain a structured time frame for calving season within the model, the number of MOET flushes is limited to three.

The number of embryos transferred is dependent on the number of embryos available and the number of synchronized recipients deemed qualified to receive an embryo. It is assumed that a round of fresh transfers accompanies every round of embryo collections. If there is an overabundance of fresh embryos compared with recipients, the left-over embryos are frozen and transferred later, in the case that there are more available recipients than fresh embryos in a later transfer round or in a specific frozen-thawed transfer session after all rounds of embryo collections have taken place. It is assumed that if unused embryos remain at the end of all transfer rounds, they are marketed as frozen embryos.

The user-defined variable for the number of recipients purchased at the start of the ET program sets the size of the recipient herd. All recipients are purchased as open, fertile females without a calf at side. The number of recipients synchronized is determined using a sampled value from the distribution for the percentage of synchronized recipients qualified for transfer to estimate the number of synchronized recipients required to match the number of available embryos. Ultimately, the number of recipients deemed qualified for transfer is computed using a binomial distribution with probability,

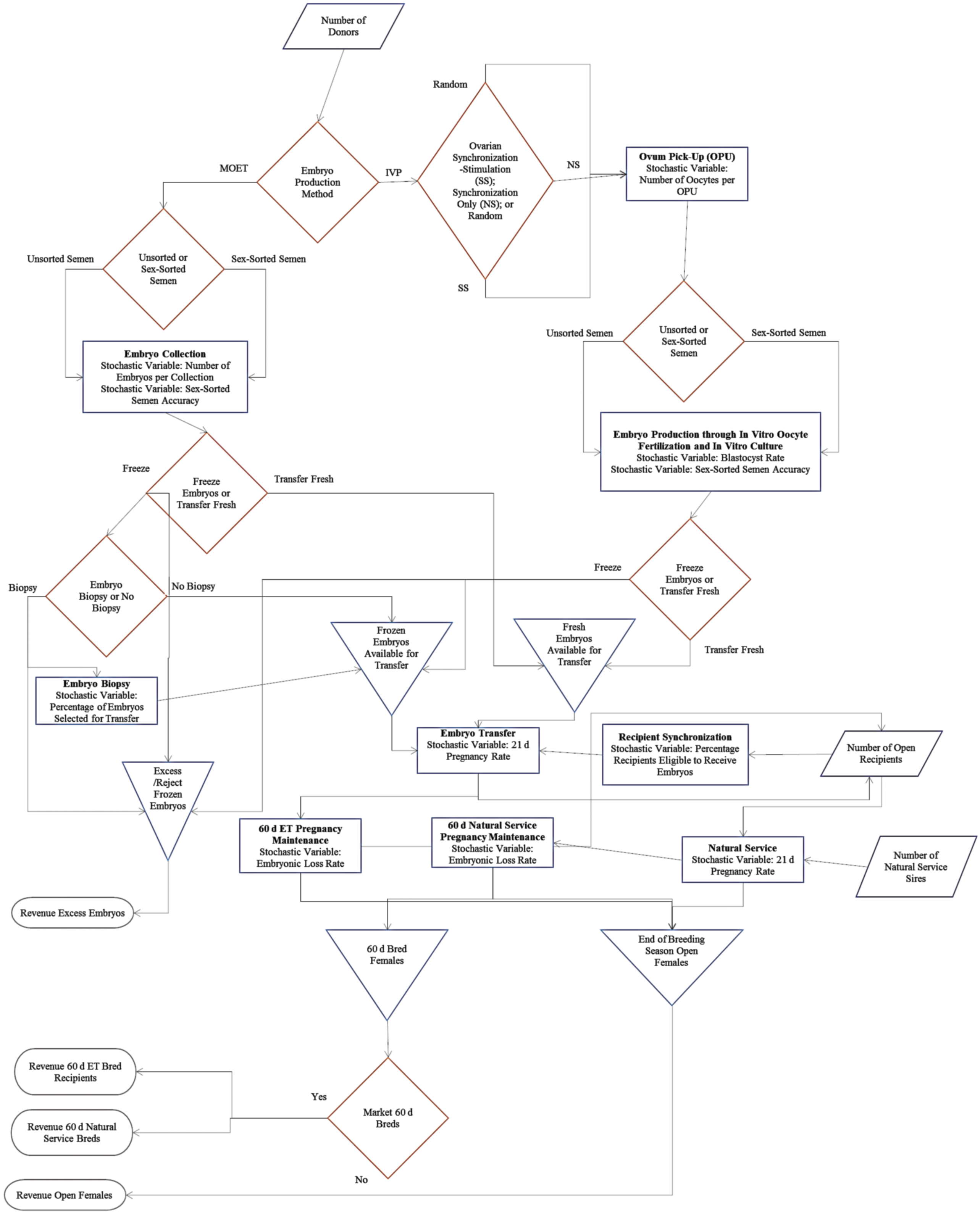

Figure 1. Depiction of ET production system model.

P, of a recipient being qualified for transfer drawn per LHS from the previous distribution.

ET pregnancy rate at 21 d (day 14 after transfer) following transfer of IVD embryos is split into fresh ET pregnancy rate and frozen-thawed ET pregnancy rate. After the establishment of a 21-d pregnancy, there is an opportunity for pregnancy loss. The distribution for the mean of pregnancy loss is separated into a distribution for pregnancy loss between days 21 and 60 of gestation and a distribution for pregnancy loss between days 60 and term.

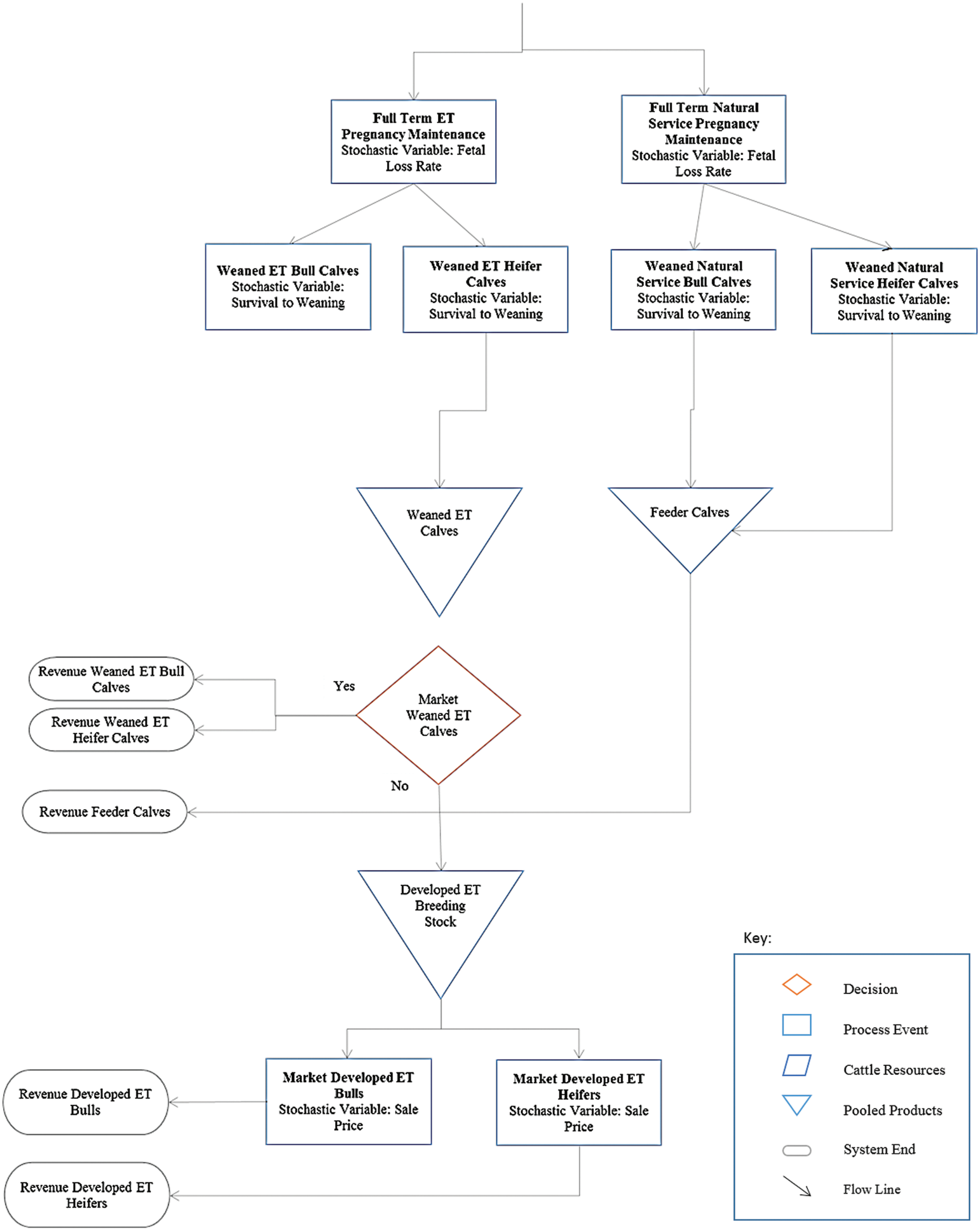

Figure 1. *Continued*

Assumed within the model, the earliest a recipient can return to estrus following a synchronized estrus, regardless of whether she cycled or received an embryo or not, is a 21-d postsynchronized estrus. Any recipient that is not pregnant at day 21 re-enters the pool of available recipients unless the ET program has concluded for the current breeding season. Recipients that experience pregnancy loss between days 21 and 60 are eligible for exposure to a natural service sire, depending on the

ET program timeframe, the time interval between transfer rounds, the transfer round that the recipients in question received transfer, and the length of bull exposure. All recipients, unless selling as a bred recipient with a confirmed 60-d pregnancy, are exposed to a natural service sire for a user-defined length of time after all transfer rounds have been completed. All recipients that experience pregnancy loss between days 60 of gestation and term are considered open at the end of the breeding season and are not eligible for natural service. Any recipient that aborts a natural service pregnancy, regardless of the period of gestation, is considered open. For all recipients, it is assumed that pregnancy is determined by cyclicity or rectal palpation/ultrasound at day 60 of gestation. Final pregnancy and open totals are a result of binomial distributions using probabilities sampled from the pregnancy establishment and pregnancy loss distribution as characterized in the "Distributions of Biological Uncertainties" section.

MOET sexed semen embryo production. All methods and calculations for simulating the production of sexed, IVD embryos are identical to those used for the simulated production of unsorted, IVD embryos, except for the probability distribution of the number of embryos generated per flush (Protocol 2). Sexed embryos are generated through the use of sex-sorted semen.

IVP embryo production. Most of the structure of the simulation model for IVP embryo production (Protocols 5 through 10) is identical to the production of MOET embryos. The major difference in the model comes with two steps specific to IVP. The first distinct step is OPU by follicular aspiration. According to the user-defined number of donors and number of OPUs per donor, the number of viable oocytes collected per OPU is sampled per LHS from the corresponding probability distribution. Next, the blastocyst development rate matching the relevant stimulation protocol and semen type is applied to the viable oocytes.

The product of the number of viable oocytes and blastocyst development rate represents the number of transferable embryos. Following transfer, distributions for the 21-d pregnancy rate, pregnancy loss between days 21 and 60, and pregnancy loss between day 60 and term are applied for either fresh IVP ET or frozen IVP ET, depending on embryo type. The remaining model organization remains constant for the differing types of embryo production.

Embryo biopsy model adaptations. In response to an industry-based question regarding the feasibility of subjecting embryos to biopsy to determine important genetic information prior to transfer and as a means of model validation, the following scenarios were simulated using the stochastic model described (Protocols 3 and 4; Figure 1). The biopsy simulation exercise also created an opportunity to demonstrate the flexibility and adaptability of the stochastic model.

In addition to adding the cost of biopsied embryos (Supplementary Table A3.1), a 10% reduction in mean pregnancy rate at full term (M. Barten, personal interview) is built into the model for recipients receiving a biopsied embryo by adjusting the distribution parameters for pregnancy rate and pregnancy loss. It is assumed that the mating used to create potential carriers is a noncarrier mated to a carrier. Additionally, scenario-dependent logic for the biopsy model can also be incorporated into the model (e.g., transfer priority of noncarrier, carrier, and potential carrier embryos).

Expenses

The structure for operation expenses in the simulation model is identical for all embryo production protocols; however, the model may or may not generate different values for the expenses described in the following sections, depending on the scenario and appropriate distribution to be sampled per LHS.

Cattle maintenance expenses—bred recipient. The costs in this section are applied to the total program expense when marketing bred recipients. According to user-defined inputs, the average of individual purchase cost, annual health program cost, and annual feed cost are compiled to calculate a total expense for donors and bulls. Unless specified otherwise, donors and bulls are considered to be owned for a full fiscal year, as it is possible and rather likely that their useful life spans more than one iteration of a bred recipient marketing program. Average individual purchase cost and health program cost are summed across the herd to generate a total recipient expense. Feed costs are allocated based on the length of time, in months, that purchased recipients are owned before marketing. It is assumed that for the marketing of owned or purchased recipients, the full time of ownership occurs in one fiscal year.

Cattle expenses—weaned calf. As in the scenario above, the cost of purchase, feed, and health program are totaled for donors and bulls. To accurately portray different feed costs for cows that calve at different times of feed and forage availability, the annual feed cost for recipient females is split between feed cost for the length of the calving season before available grazing (see "Weaned calf feed costs—pregrazing season calving" section) and the rest of the fiscal year. Annual feed costs are only applied to open females for the part of the fiscal year that they are still in the herd. In year 1 of the program, purchase costs of recipients are totaled with feed and health program costs. For subsequent years of the ET program, recipient replacement cost (the cost of replacing open recipients to fit the recipient herd size defined by the user) is combined with recipient maintenance costs to generate a total recipient expense.

Weaned calf feed costs—pregrazing season calving. Although calves born at the beginning of calving season tend to be heavier at weaning (assuming all calves are weaned on the same day, as in this model), there is also a potential trade-off in the cost of required nutrients for early calving cows, depending on the relationship between calving season and the availability of forage and/or cost of feed. By incorporating user-defined inputs for ration cost, expected cow DMI for the third trimester of gestation, expected cow DMI postpartum, and calving season length (in days) before the grazing season, the cow feed costs associated with calving at different times within the calving season can be estimated. The number of bred recipients from each respective ET round and natural service cycle dictate the calving dispersion throughout the calving season. Thus, the number of third trimester and postpartum days before the grazing season can be determined based on when conception occurred during the breeding season. The resulting total pregrazing season, calving season cost is built into the annual recipient feed cost that is used in the "Cattle expenses—weaned calf" section.

Donor protocol cost. The number of doses of exogenous reproductive hormones and the cost per dose, as user-defined, are combined over the total number of superovulation protocols in one ET breeding season. Total semen cost is equal to cost per dose multiplied by doses required, and total embryo collection cost depends on number of procedures and cost per procedure. If there is an overabundance of embryos compared with recipients, freezing costs are also included. Furthermore, costs from nonveterinary labor hours required for superovulation and embryo collection are described in this section of the model.

Recipient protocol cost. The total recipient protocol cost depends on user-defined values for exogenous reproductive hormones, ET, pregnancy determination, pregnancy sex determination, and nonveterinary labor, combined with the required amount of each resource.

Weaned calf preconditioning cost. Several user-defined costs go into the estimation of weaned calf preconditioning costs. They include daily backgrounding cost per head, vaccine cost per head, and treatment cost per head. The total number of head that goes through the preconditioning program prior to marketing is determined from the simulated number of calves that survive to weaning. Total backgrounding head days are calculated by multiplying the number of weaned calves by the user-defined preconditioning days. It is assumed that postweaning mortality is zero.

Bull/heifer development cost. Development expense is determined by coupling the vaccine cost per head, treatment cost per head, miscellaneous development cost per bull (breeding soundness exam, ultrasound, registration, etc.), miscellaneous heifer development cost per heifer (Brucellosis vaccination, reproductive tract score, registration, etc.), daily bull development cost, and daily heifer development cost with the number of bulls and heifers undergoing development and the development duration (days).

It is assumed that all natural service sired calves are commercial; thus, all natural service sired calves are marketed after preconditioning according to weight and the feeder calf pricing slide within the model. The user-defined cull rate determines the number of ET culls with respect to a simulation based on n (number of ET bulls and ET heifers) number of Bernoulli trials. Within the model, all cull calves are marketed as preconditioned feeder calves. The expense associated with the preconditioning of naturally sired and cull calves is determined in the same manner as described in the "Weaned calf preconditioning cost" section.

Total expenses—owned donors. Expenses from the preceding sections are compiled for all scenarios in which the ET program under consideration owns the donor females used in the ET program. The specific costs included in the total program expense depending on embryo production strategy, ownership of recipients, and marketing strategy for each scenario.

Total expenses—custom recipient. Again, according to the specifics of a given scenario, previously described expenses are combined for all scenarios in which the ET program does not own any donor females but does own and manage a recipient herd. The particular expenses that are incorporated into the total depend on the embryo production or purchase strategy and the marketing scheme.

Revenues

The following sections describe calculations corresponding to revenue streams. The basic simulation model structure is identical for all production protocols, but the values generated depend on the scenario and LHS sampling scheme.

Embryo revenue. If embryo production out-paces recipient availability, excess embryos are frozen and marketed at a user-defined price per embryo. Different prices may be assigned to unsexed embryos, bull embryos, and heifer embryos.

Bred recipient revenue. It is assumed that all bred recipients are marketed after day 60 of gestation at a value defined by the model user. An expected individual market value is assigned to a pregnant recipient carrying an embryo of unknown sex, a pregnant recipient carrying a bull embryo, a pregnant recipient carrying a heifer embryo, a pregnant female carrying a naturally sired calf, and an open female. Market uncertainty is not accounted for regarding revenue from the sale of bred or open females. Sale price is fixed. The number of recipients of each pregnancy type is determined for each model iteration. A binomial distribution within the model determines the number of ET pregnancies of each sex for each iteration of the simulation. For ET production using unsexed semen, an extra veterinary expense is applied for determination of the sex of pregnancy.

Weaned calf revenue. The market value per weaned calf is determined by the feeder calf slide (prices adjustable per current market), a user-defined premium for ET bull calves and another user-defined premium for ET heifer calves. The price slide is based on the current market price of feeder steers. Heifer calves are discounted to 92% of the price per pound of steer calves (Schulz et al., 2009). It is also possible to base an ET calf premium on dollars per pound. All calves are weaned on the same day. Thus, to account for differences in weaning weight, ET rounds and natural service cycles are split according to expected calving date to form calving groups. Weaning weights are determined by the user-defined growth expectations of calves and the anticipated calf age (in days) at weaning. Growth expectations in terms of ADG (pounds per day) are deterministic variables. All weaned calves undergo a user-defined preconditioning period (days). Calf weight following preconditioning is a product of the number of days of preconditioning and the expected calf performance, as defined by the model user.

The number of calves weaned within each calving group is calculated from the number of females carrying a pregnancy to term within each calving group and the percentage of calves that survive to weaning. The number of calves that survive to weaning is based on a binomial distribution with probability of survival, P, and number of pregnancies, n, maintained to term. For unsorted semen, a binomial distribution also determines calf sex where $P = 0.5$ is the probability of a bull calf and n is the number of pregnancies maintained to term. By combining the applicable calf sex and weight with its associated price per pound and premium for ET calves, the individual calf value is determined.

ET bull/heifer development revenue. ET bull and ET heifer development revenue accounts for ET programs that develop ET calves beyond preconditioning and sells them in a production sale or similar marketing strategy. All naturally sired calves are sold after preconditioning, in the same manner as described in the "Weaned calf revenue" section. A user-defined cull rate specifies the appropriate percentage of ET calves of each sex to be sold after preconditioning. The weight associated with the cull calves is the average of the entire group of ET calves at the end of the preconditioning phase. All culling of ET calves is done at the conclusion of preconditioning. The number of ET calves of each sex is determined using a binomial distribution, in the same manner as described in the previous section.

The distributions of the average price per ET bull and per ET heifer, respectively, can be estimated by inputs based on expectations or can be constructed using past sale data. A random value, sampled per LHS, drawn from the price distribution for ET bulls and the price distribution for ET heifers is multiplied by the number of ET bulls and ET heifers, respectively, to generate a total ET calf value for each iteration.

Total revenue. Revenue streams are combined for the scenario in question depending on marketing strategy. Potential marketing schemes include sale of embryos, sale of bred recipients, sale of weaned/preconditioned calves, and sale of developed ET bulls and developed ET heifers. If the operation in question owns the donor females, the revenue from the sale of any excess embryos is always combined with revenue from the sale of live animals. Within this model, an operation may only market live animals by one method within a particular scenario, except for the sale of naturally sired calves and cull ET calves immediately following preconditioning in a developed ET bull/heifer marketing strategy.

Economic Values

Annual cash flow. Total expenses and total revenues are calculated on an annual basis. Excluding initial investment expense, the total expenses and total revenues for a given scenario are combined to yield an annual cash flow figure. Regarding the sale of ET progeny, whether sold after preconditioning or development, it is assumed that revenue occurs in the same fiscal year as the birth of said calf. The final annual cash flow figure can then be used in NPV calculations.

Net present value, annuity equivalent net present value, return on investment. NPV is used to measure ET program profitability. It is defined as follows:

$$\mathrm{NPV} = \sum_{n=1}^{N} \frac{\mathrm{ANCF}_n}{(1+i)^n} + \frac{\mathrm{RESID}_N}{(1+i)^N} - \mathrm{INV};$$

where N = life of investment; i = discount per interest rate, ANCF = annual net cash flows, RESID = residual value, and INV = original investment cost and is used to put ET program profitability into economic terms. $\boldsymbol{N}$ and $\boldsymbol{i}$ are user-defined variables (Supplementary Table A2.12); RESID and INV are calculated by multiplying the number of donors, recipients, and bulls by their associated, user-defined residual value per head and initial value per head, respectively. ANCF values are derived from the annual cash flow section previously described.

Annuity equivalent NPV is represented by the following equation:

$$\mathrm{ANPV} = \mathrm{NPV}\left[\frac{i}{1-(1+i)^{-N}}\right];$$

where i = discount per interest rate and N = investment life in years.

ROI is calculated as $\mathrm{ROI} = \frac{R-E}{E}$; where R = total revenue over the life of the investment and E = total expense over the life of the investment.

Each simulation replication for a particular ET protocol produces a value for the NPV, ANPV, and ROI. Because multiple replications are performed, the result is a frequency and/or probability distribution for NPV, ANPV, and ROI under each protocol.

Assumptions

Although many assumptions have already been mentioned in previous discussion, the following list contains all assumptions pertinent to the model.

General model assumptions. The model includes the following general assumptions: no correlation between traits and measurements; all recipients enter the system as purchased opens; all purchases occur on day 1 of fiscal year; all calves are weaned the same day; if a calf lives to weaning, it lives through development; and bulls have a 3-yr breeding life.

Reproductive model assumptions. The model includes the following reproductive assumptions: healthy donors recipients and bulls; 21-d estrous cycles; ET occurs on day 7 following the onset of estrus; recipients are synchronized within 24 h or donor; normally cycling donors and recipients; ET program is seasonal, not continuous; and MOET IVD is limited to three flushes per breeding season.

Embryo production model assumptions. The model includes the following embryo production assumptions: recipients that return to estrus on day 21 re-enter available recipient population, depending on ET round and time interval between flushes or OPUs; ET recipients that experience pregnancy loss between days 21 and 60 of pregnancy are eligible for natural service, depending on the interval between transfers and length of bull turnout; ET bred recipients that experience pregnancy loss between day 60 and term are not eligible for natural service; and natural service bred recipients that experience pregnancy loss at any point after day 21 of gestation are not eligible for another natural service conception.

Revenue model assumptions. The model includes the following revenue assumptions: bred recipients are sold carrying a minimum 60-d pregnancy with no calf at side, and calf development revenue occurs in the same fiscal year that calves are born.

Expense model assumptions. The model only accounts for variable expenses between the production strategies or embryo production methods in question. Thus, the following expenses are excluded: overhead or whole ranch costs, facilities, non-ET veterinary costs (pulling calves, emergencies, etc.), equipment expense, and taxes.

Distributions of Biological Uncertainties

To allow for probability distributions to be built into an Excel workbook and values drawn from the said distributions through the simulation of an Excel-based model, @Risk 7.5 was used. Supplementary Table A1.1 describes the distributions generated for each of the stochastic variables (Aherin, 2017).

Deterministic Variables

Accompanying the stochastic variables characterized by the distributions previously described are the user-defined deterministic variables listed in Supplementary Tables A2.1–A2.13. The values used in the current simulation study are included in the tables.

A multitude of variables currently represented deterministically could also be represented stochastically, if such a feature is deemed pertinent to the usefulness of the model. Examples include fair market values (Supplementary Table A2.5), treatment cost per head (Supplementary Table A2.10), and anticipated calf performance (Supplementary Table A2.9).

RESULTS AND DISCUSSION

Although several economic value predictors for ET programs already exist (Beltrame et al., 2010), the opportunity remains to create more applicable models for *Bos taurus* beef production and varying marketing avenues in the United States. A strength of the proposed simulation approach is that it makes it possible to examine the range of potential outcomes for a given production strategy with a combination of expediency, negligible resource use, and number of trials that could not be replicated in the field. Mean values of economic and production measures are important, but the distributions of biological uncertainties embedded within the model cause many output distributions to vary greatly in shape, often straying far from a normal distribution. Thus, it is possible for distribution means and most likely outcomes to diverge from one another substantially. Therefore, equal, if not greater, attention should be paid to the percentiles and probabilities associated with each output distribution. Perhaps, the greatest measurement of financial risk is the probability of negative return. Furthermore, a deeper investigation into the varying production outputs that causes differences between the economic outputs of the scenarios in question is feasible, although not described in the scope of this article. Each individual firm may consider risk differently and operate at a different level of risk aversion. Differing scenarios and production strategies could also cause substantial changes in economic output distributions and rankings of ET methodologies.

CONCLUSIONS

Inherent to the identity of the beef industry is the variation of environment, cattle type, and management practices between operations. Thus, a critical aspect of the stochastic model described and applied in the preceding pages is the ability to incorporate user-defined variable values, specific to an individual operation, as parameters for the program in question. The results associated with each ET methodology in the example scenario discussed may differ drastically with individualized changes in production strategy, cost structure, and anticipated revenues. The stochastic elements of the model create a more realistic outlook than the use of means in deterministic models, as distributions defining the biological uncertainty for a multitude of reproductive outcomes are incorporated into the model. The core function of this model should be as a consultative tool using the generated distributions of NPV, ANPV, and ROI as an aid in the assessment of the economic risk linked to a user-defined MOET or IVP program.

This model does not account for the increased magnitude and rate of genetic gain that is possible through ET and the potential long-term impact those genetic improvements may have on a breeding program. Accounting for the long-term economic impact of accumulated improvements or changes in production efficiency is a potential next step in analyzing the economics of ET. This model could serve as a foundational template for that opportunity.

The pace of change in the IVP industry is rapid enough that many advances are not reported in the scientific literature before being implemented in industry. Furthermore, it is likely that IVP companies may regard technological advancements as trade secrets that yield a competitive advantage in the marketplace. Thus, a challenge in the application of this model is creating and maintaining an accurate representation of expected production outcomes from the most current ET practices.

The numerical and logical analysis afforded through the stochastic simulation of alternative scenarios through this model allows for in-depth assessment of ET programs not previously available. The caveat is that any model, no matter how robust, will never be completely accurate, as all are a simplified version of a complicated reality. That said, there is ample opportunity for the commercial application of this stochastic model to complement the deterministic, instinctive, and experience-based elements of the decision-making process pertaining to the prediction of the economic outcome of an ET program, through methodology that the ET industry has not fully exploited.

SUPPLEMENTARY DATA

Supplementary data are available at *Translational Animal Science* online.

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