Digital Twins for Salmon Wellbeing: A Tutorial Series

Based on Giske et al. (2025)

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Annotated Reference Guide

This section provides an annotated guide to key references organized by topic area, highlighting their relevance to digital twin implementation for salmon wellbeing.

Core Frameworks and Concepts

- **Giske et al. (2025)** [31] – The foundational paper on salmon digital twins that outlines the theoretical basis for monitoring and predicting salmon wellbeing through computational modeling.
- **Budaev et al. (2020)** [10] – Introduces a computational architecture for modeling animal sentience, emotions, and wellbeing that serves as a basis for digital twin development.
- **Budaev et al. (2019)** [11] – Bridges ecology and subjective cognition in animal decision-making, providing a framework for implementing cognition in digital twins.
- **Budaev et al. (2018)** [9] – Introduces the AHA (Adapted Heuristics and Architecture) cognitive architecture for Darwinian agents that can be adapted for salmon digital twins.

Fish Cognition and Emotions

- **Giske et al. (2013)** [30] – Examines how emotions affect adaptive behavior in fish, providing insight into implementing emotional systems in digital twins.
- **Vindas et al. (2016)** [70] – Investigates serotonergic activation in farmed salmon, distinguishing between adaptation and pathology in stress responses.
- **Vindas et al. (2014)** [71] – Explores dopaminergic and neurotrophic responses in salmon when expected rewards are omitted, relevant for implementing prediction errors in digital twins.
- **Cabanac (1992)** [13] – Presents the concept of pleasure as a common currency for decision-making across species, informing the implementation of wellbeing assessment.
- **Mendl & Paul (2020)** [44] – Reviews current understanding of animal affect and its role in decision-making, providing a foundation for modeling emotional states.
- **Crump et al. (2020)** [16] – Examines the role of emotion in animal contests, offering insights into modeling social interactions and competitive behavior.

Consciousness and Sentience

- **Ginsburg & Jablonka (2019)** [29] – Comprehensive exploration of the evolution of consciousness and learning, providing theoretical foundation for digital twin cognition.
- **Low et al. (2012)** [39] – The Cambridge Declaration on Consciousness, affirming the presence of consciousness in non-human animals including fish.
- **Andrews et al. (2024)** [3] – The New York Declaration on Animal Consciousness, updating scientific consensus on animal consciousness.
- **Barron & Klein (2016)** [6] – Examines what insects can tell us about consciousness origins, providing insights for implementing minimal consciousness models.
- **Feinberg & Mallatt (2016)** [22] – Explores the ancient origins of consciousness and how the brain created experience, informing digital twin cognitive models.
- **Seth (2021)** [61] – Presents new scientific approaches to understanding consciousness, offering perspectives for modeling subjective experience.
- **Zacks et al. (2022)** [76] – Investigates the evolution of imaginative animals and episodic-like memory, crucial for modeling prediction in digital twins.

Digital Twins and Computational Modeling

- **Rasheed et al. (2020)** [52] – Reviews digital twin values, challenges, and enablers from a modeling perspective, providing practical implementation guidance.
- **VanderHorn & Mahadevan (2021)** [69] – Offers a framework for digital twin characterization and implementation applicable to biological systems.
- **Tao et al. (2022)** [67] – Presents comprehensive approaches to digital twin modeling that can be adapted for biological applications.
- **Eliassen et al. (2016)** [20] – Demonstrates how to model proximate architecture for decision-making from sensing to emergent adaptations.
- **Giske et al. (2014)** [32] – Shows how emotion systems promote diversity and evolvability in evolutionary models, informing genetic algorithm implementation.
- **Andersen et al. (2016)** [1] – Details the proximate architecture for decision-making in fish that can be directly implemented in digital twins.
- **Grimm & Railsback (2013)** [34] – Provides foundational methods for individual-based modeling in ecology applicable to digital twin populations.

Neuroscience and Decision-Making

- **LeDoux (2012)** [38] – Rethinks the emotional brain, introducing concepts like survival circuits central to digital twin decision architecture.
- **Anderson & Adolphs (2014)** [2] – Presents a framework for studying emotions across species that can be applied to salmon emotion modeling.
- **Schultz (2024)** [59] – Examines dopamine mechanisms for reward maximization, crucial for implementing learning in digital twins.

- **Friston et al. (2010)** [26] – Introduces free-energy formulations for action and behavior that inform prediction-based decision making.
- **Peters et al. (2017)** [49] – Explores how uncertainty and stress are processed by the brain, informing stress modeling in digital twins.
- **McNamara & Houston (1986)** [42] – Classic paper on common currency for behavioral decisions that informs wellbeing-based decision models.
- **McNamara & Houston (2009)** [41] – Discusses integrating function and mechanism in behavioral models, relevant for digital twin architecture.

Stress, Allostasis, and Boredom

- **Korte et al. (2007)** [37] – Presents a new animal welfare concept based on allostasis that informs wellbeing modeling in digital twins.
- **Sterling (2012)** [64] – Details allostasis as a model of predictive regulation central to digital twin physiological modeling.
- **McEwen et al. (2015)** [40] – Explores mechanisms of stress in the brain that can be implemented in digital twin stress response systems.
- **Wingfield et al. (1998)** [75] – Introduces the "emergency life history stage" concept relevant for modeling extreme stress in digital twins.
- **Meagher (2019)** [43] – Examines whether boredom is an animal welfare concern, providing foundation for modeling boredom in digital twins.
- **Burn (2017)** [12] – Presents a biological perspective on animal boredom with suggestions for scientific investigation.
- **Spruijt et al. (2001)** [63] – Offers a concept of welfare based on reward mechanisms applicable to digital twin wellbeing assessment.

Environmental Enrichment and Learning

- **Salvanes et al. (2013)** [57] – Demonstrates how environmental enrichment promotes neural plasticity and cognitive ability in fish.
- **Zupanc (2006)** [77] – Explores neurogenesis and neuronal regeneration in adult fish brains, relevant for modeling brain development.
- **Näslund et al. (2019)** [46] – Investigates how rearing environment affects brain development in hatchery-reared Atlantic salmon.
- **Arechavala-Lopez et al. (2022)** [4] – Reviews environmental enrichment in fish aquaculture, offering practical applications.
- **Folkedal et al. (2010)** [24] – Studies habituation rates in Atlantic salmon, providing data for learning implementation.
- **Bratland et al. (2010)** [8] – Examines the transition from fright to anticipation in salmon, informing predictive models.
- **Dumitru & Opdal (2024)** [18] – Discusses how rearing environment defines brain plasticity, challenging the mosaic model of brain evolution.

Aquaculture Welfare and Management

- **Stien et al. (2013)** [65] – Introduces the Salmon Welfare Index Model (SWIM 1.0) that catalogs key welfare indicators.
- **Pettersen et al. (2014)** [50] – Presents SWIM 2.0, an extended model for overall welfare assessment of caged Atlantic salmon.
- **Overton et al. (2019)** [48] – Reviews salmon lice treatments and mortality in Norwegian aquaculture, highlighting welfare challenges.
- **Bracke et al. (1999)** [7] – Presents overall animal welfare assessment based on needs and expert opinion.
- **van de Vis et al. (2020)** [72] – Compares welfare of fishes in different production systems, providing benchmarks for digital twin validation.
- **Dawkins (2023)** [17] – Discusses farm animal welfare beyond "natural" behavior, offering perspectives for defining appropriate wellbeing metrics.
- **Segner et al. (2019)** [60] – Presents FAO's approach to welfare of fishes in aquaculture, providing regulatory context.

Precision Aquaculture and Monitoring

- **Føre et al. (2018)** [25] – Introduces precision fish farming as a framework for improving production in aquaculture.
- **Mustapha et al. (2021)** [45] – Reviews roles of cloud computing, Internet of Things and AI in sustainable aquaculture.
- **Royer & Pastres (2023)** [54] – Demonstrates data assimilation for efficient management of dissolved oxygen in aquaculture.
- **Eguiraun et al. (2018)** [19] – Applies Shannon entropy to construct a biological warning system model for fish monitoring.
- **Neethirajan (2021)** [47] – Reviews the use of AI in assessing affective states in livestock, with potential applications for fish.

3Rs and Ethical Considerations

- **Russell & Burch (1959)** [56] – The original work introducing the 3Rs (replacement, reduction, refinement) principles.
- **Grimm et al. (2023)** [33] – Discusses advancing the 3Rs through innovation, implementation, ethics, and society.
- **Hawkins et al. (2011)** [35] – Provides guidance on severity classification of scientific procedures involving fish.
- **Sloman et al. (2019)** [62] – Examines ethical considerations in fish research, offering guidelines for digital twin development.
- **Collins & Part (2013)** [15] – Reviews approaches to modeling farm animal welfare, including methodological considerations.

- **Pielke (2007)** [51] – Introduces the concept of the "honest broker" in science and policy that digital twins could fulfill.
- **Gaffney & Lavery (2022)** [27] – Identifies research gaps in salmonid welfare that digital twins could address.

Machine Learning and Data Science

- **Reichstein et al. (2024)** [53] – Demonstrates early warning of complex risk with integrated AI, applicable to wellbeing monitoring.
- **Schölkopf et al. (2021)** [58] – Discusses approaches to causal representation learning applicable to digital twin modeling.
- **Elkan (2001)** [21] – Explores foundations of cost-sensitive learning for handling imbalanced wellbeing states.
- **Garcia & Fernández (2015)** [28] – Provides a comprehensive survey on safe reinforcement learning applicable to digital twin development.

Robustness and Systems Approaches

- **Kitano (2004)** [36] – Explores biological robustness concepts applicable to digital twin design.
- **Fernandez-Leon (2011)** [23] – Examines evolving cognitive-behavioral dependencies for robustness in situated agents.
- **Ruiz-Mirazo et al. (2004)** [55] – Discusses autonomy and open-ended evolution as universal life properties relevant to digital twin design.
- **Thompson (2007)** [68] – Presents a biology and phenomenology approach to mind that can inform digital twin consciousness models.
- **Colditz (2023)** [14] – Proposes a biological integrity framework for describing animal welfare and wellbeing.

Methodological Resources

- **Way (2017)** [73] – Discusses Feynman's famous quote "What I cannot create, I do not understand" in the context of biological modeling.
- **Taborsky et al. (2021)** [66] – Presents an evolutionary theory of stress responses that can inform digital twin stress models.
- **Wingfield (2013)** [74] – Explores comparative biology of environmental stress and ability to cope with changing environments.
- **Barrett (2020)** [5] – Provides seven and a half lessons about the brain with implications for cognitive modeling.

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