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SUMMARY – The growth of the marine aquaculture sector, and increasing interest and demand in using less protected offshore waters has brought about a range of opportunities and challenges. A number of production systems are already being developed, some of which are now reaching the technological and operational point where they may be considered to be truly offshore systems. However, many other systems and installations have been found to be inadequate for intended objectives, and in circumstances where capital and operating costs must be kept within strict boundaries, excessive damage and loss may create significant disincentives to development. This paper outlines the technical and operational criteria which must be considered for effective offshore mariculture, emphasizing the need to understand the full systems context to ensure that production can be achieved in a secure and cost-effective manner. Implications for development planning are also discussed.

Key words: Marine aquaculture, systems, cages, economics, development.

RESUME – *"Potentialités de la mariculture en mer ouverte". La croissance du secteur de la mariculture, ainsi que l'intérêt et la demande grandissants pour l'utilisation des eaux côtières moins protégées, a donné lieu à toute une série d'opportunités et de défis. Plusieurs systèmes de production sont en cours de développement, dont certains maintenant sont parvenus à un stade technologique et opérationnel tel qu'ils peuvent être considérés vraiment comme des "systèmes offshore". Cependant, beaucoup d'autres systèmes et installations se sont avérés inappropriés pour les objectifs visés, et sous des circonstances où les frais d'investissement et de production doivent être tenus dans des limites strictes, des dommages et pertes excessifs pourraient créer de grands problèmes pour le développement du secteur aquacole. Cette présentation décrit les critères techniques et opérationnels qui doivent être considérés pour une mariculture "offshore" performante, en soulignant la nécessité de comprendre le contexte complet des systèmes, pour s'assurer que la production soit menée de manière à avoir un bon niveau de sécurité et qu'elle soit efficace pour le coût. Les implications pour la planification du développement sont aussi discutées.*

Mots-clés : *Aquaculture marine, systèmes, cages flottantes, économie, développement.*

Introduction

Though artisanal cage culture has a long tradition (Beveridge, 1996), modern cages have only been developed over the last two decades, and units suitable for more challenging conditions have only become feasible in the last 10 years. A range of offshore cages –from concepts to fairly well-tested systems– is potentially available for the industry, and a small but steadily increasing share of output is starting to accrue to offshore production. The following sections describe the range of cages currently in use and their level of development. Environmental and other policy decisions, coupled with a steady pressure for economies of scale, are increasingly focusing interest and development efforts towards expansion in offshore zones (Muir and Young, 1997). As enterprises and investors become more confident, and as suppliers of goods and services become more involved in the challenges of offshore production, we might expect greater development of designs, more proven systems, and more investment and production.

However, the common experience of most operators in the aquaculture industry is that offshore production carries considerable risk, and although the track record of specific units is becoming more positive, the criteria for success, in conditions which are environmentally, technically and financially challenging, are as yet poorly defined (see, e.g., Kuo and Beveridge, 1990; Willinsky and Huguenin, 1996). The options presently available are still rather limited, and of uncertain effectiveness, and a considerable degree of local modification and adaptation is common, often involving substantial additional risk and expense. The potential for offshore aquaculture is therefore as yet far from clear, and there are several key, inter-relating issues to consider: (i) can complete offshore systems be defined and developed?; (ii) can these be developed and operated in a cost-effective manner?; (iii) will they be suitable for regional conditions?; (iv) will there be an appropriate policy environment?; and (v) will there be the appropriate market and investment conditions to stimulate their use?

The following sections will consider some of these issues and their implications.

A systems perspective

As shown in Table 1, offshore aquaculture production comes about not just through the design and selection of a holding unit, and the placing of this unit in a particular location, but through the combination of a number of interacting factors (Muir, 1996). Furthermore, choices for this combination of factors would usually be shaped by a single objective –profitable production, which requires productivity, reliability, market focus and competitiveness over the periods for which investment decisions would need to be made.

Table 1. Offshore aquaculture as a system

Component/element	Key issues and relationships
Species	Individual/group behaviour, tolerances, disease, growth, variabilities
Site/environment	Stock conditions, infrastructure/access, wave climate, tidal currents, biohazards
Holding unit	Containment/separation, shape, position, attachment, access, bioresponse
Positioning assembly	Location, access, attachment, dynamic response
Human inputs	Access, confidence, knowledge, care, safety, effect, efficiency
Stock growth	Inputs, quality, transport, storage, control, dispersion, efficiency
Stock management	Access, metrology/data, control response, focus
Product flow/storage	Quantities, quality, loads, balances, position, movement
Security	State, integrity, feedback, response conditions
Market output	Timing, quantity, uniformity, variety, quality connotations
Business/economic	Decision context, input and output conditions

The development of cage designs from a range of technical sources, and the absence of a "systems" perspective, recognizing the functional interdependence of stocks, holding units, nets, moorings, feeding, environment, service systems and market outputs, has meant that most present forms of offshore production represent rather imperfect compromises between competing constraints and objectives. The design of cages and mooring systems together, and the close matching of these with specific site conditions have for example only recently come about. However, there are very few examples of systems which have been designed specifically as a holding unit/mooring structure composite, or of strategic siting decisions being taken on the basis of species and system interactions, and of the wider management implications. In most cases, sites are chosen or allocated first, and the system and operating procedures developed in consequence.

Based on the definitions developed in Table 1, more specific criteria could be established for individual components, improving their mutual compatibility. This is not to suggest that there would a single ideal solution, but simply indicates that more could be done –through the design process, rather than through the development problems of the producer– to improve the overall effectiveness of offshore aquaculture. By using further analyses (see, e.g., Rudi *et al.,* 1996) it should be possible to determine the potential operational constraints, and their significance, in establishing an aquaculture system in an exposed location. Table 2 provides a summary of how these criteria might evolve, and identifies the important criteria for effectiveness and the typical design and commercial objectives related to these. In addition, a number of environmental impact issues may have to be considered, primarily defined from the perspective of the system in which the aquaculture project is located, rather than the objectives of the aquaculture operation alone (see, e.g., Goldgerg *et al.,* 1996).

Table 2. Sub-system criteria

Subsystem	Criteria/functional objectives
Species	Predictability of response, tolerance within system limits, minimal intervention
Site/environment	Normal and extreme states defined, growth support, access, legal protection
Holding unit	Size, shape stability, integrity, redundancy (failsafe provision), known responses
Position assembly	Movement limits, stress dispersion, relocation function, redundancy, access
Human inputs	Ergonomic effectiveness, key information access, extreme state operation
Feed delivery	Non-limited availability, FCR and growth limits, minimal loss
Stock management	Growth performance, production plan targets
Product flow/storage	Non-limited availability
Security/risk	High integrity, recovery potential, insurability
Market output	Defined and predictable product quantities, grades, quality
Business/economic	Positive risk-discounted return across business scenarios

Current status of offshore system design

Though the above criteria can be described, these are rarely used specifically in current developments, though producers' own management objectives may include at least some elements, particularly those concerning feed performance, stock management, market output and business/economic criteria. However, unless producers are using extremely well developed management information and decision support systems, based on accurate growth and survival predictions, the various trade-offs in management choice (e.g., between growth and food conversion, between grading frequency, operating cost and stock performance) are largely subject to individual management preferences. In very few cases are these production criteria specifically linked to site and design criteria, and the basic assumption is usually adopted that the physical system provides an adequate basis for management, unless specific constraints emerge. In these cases, decisions can be made as to whether such constraints are to be tolerated, or whether they can be overcome or circumvented.

Table 3 summarizes the key holding unit approaches, as defined according to structure positioning characteristics (see also Scott and Muir, this volume), and their present state of development with respect to the criteria suggested above.

Potential system options

The movement of production from sheltered and near-shore locations to genuine offshore systems will require a number of essential transformations, from:

(i) Systems which are essentially human-sensory oriented to those which are machine-oriented.

(ii) Systems which are modest in scale, with varying degrees of artisanal/local fabrication, and non-specific to location and production aims to those which are large, highly engineered, and probably tailored to specific site, species and production conditions.

At present, though some systems operate in potentially exposed conditions, very few are designed for fully open sea conditions, in which a majority sea state condition may prevent normal access of the form currently expected in aquaculture management. The progression of aquaculture has been such that incremental movement offshore proceeds as structures are gradually improved in design, strengthened, tested and proved, and as operating systems and procedures are developed. This tends to create the context in which each new development is largely based on previous developments and to some extent, on preconceptions of how an ideal production system might be defined. In a field such as aquaculture, which is commonly characterized by high risk levels, this conservatism is fully understandable.

Table 3. The potential of present systems

Structure	Current status	Potential development
Floating		
Flexible	Widely used in many offshore locations; cheapest and simplest	Increase in size, standardize moorings, better service and management systems, possible service platforms
Rigid	Small number installed, high cost constraints	Possibly only through subsidy and/or very large scale installations, or as platforms for lower cost systems
Semi-submersible		
Flexible	Initial installations have shown promise, with low cost potential	Improve automation, prove long term durability, accessibility, and effectiveness in multiple deployments and range of species
Rigid	Several installations have proven effective; medium to high costs	Maintain function while reducing materials/costs and/or improve efficiency and amortized cost -possibly develop as central platforms
Submersible		
Rigid	Experimental only, but concept capable of development	Needs to be tested, and to demonstrate effectiveness of deployment and stock management. Automated operations and monitoring required

If however a more open question is presented of having to find ways in which stock can be separated, owned, cared for to varying degrees –yet have available the wide access and capacity represented by open waters, the potential solutions may be broader than those defined by current practice. Though purposed designed structures may be relevant, a more fundamental change would be to contain stocks in non-solid systems, using various stimuli and learning techniques. Closer to present day approaches, the use of large structures for other purposes may permit the development of relatively simple aquaculture structures in artificially sheltered conditions. As shown in Table 4, a variety of options might be considered, various elements of which could be linked together.

Economic issues

Though a complete census is not available, manufacturers claims would suggest that at least 500 offshore-type cage units have been sold, though true offshore operating conditions are probably only characteristic of a small number of these. Assuming 200 units of an average 2500 m^3, with an annual yield of 10 kg/m^3/yr, this represents some 5000 t of annual production, a very small percentage of current intensive cage culture production. The capital costs of a range of cage systems are described elsewhere in the texts, and one of the key issues with respect to future potential would be the competitiveness of future offshore development (see, e.g., Stephanis, 1995; Paquotte *et al.,* 1996). As indicated in Fig. 1, if future offshore locations are significantly more expensive to develop, the potential for expansion may be limited.

Table 4. Potential system options

System options
- Release, management and collection with variously defined stock rearing areas
- Multipurpose shelter systems, with range of holding systems/transfer options
- Standard shore base, large transfer and operating vessels, simple holding systems
- Standard shore base, medium size transfer and operating vessels, structured holding systems
- Minimal shore base, medium size transfer vessels, fully developed long-term service platform
Service structure options
- Floating – modified barge/vessel, specially designed, or attached/linked to holding system
- Fixed – separate or linked to holding system
- Submerged
Positioning options
- Individual moorings
- Linked moorings
- Dynamic positioning
Operational options
- Manual
- Mechanically assisted
- Semi-automated
- Fully automated

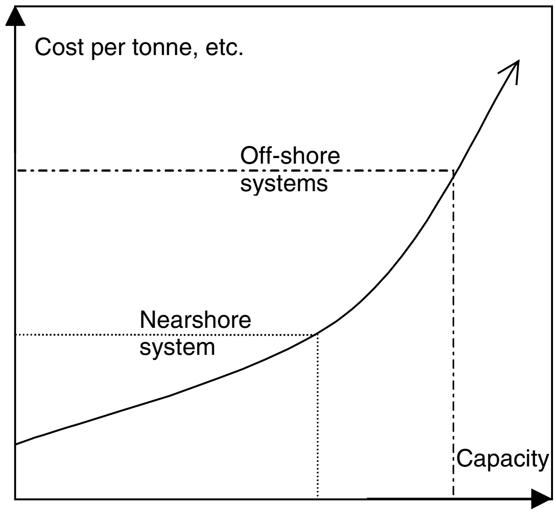

Fig. 1. Developed capacity and cost.

Other key factors would include the risk –both the perceived risk– e.g., for potential investors, insurers, and the actual risk as it develops over cumulative experience. If total risk levels are similar for inshore and offshore production, then standard comparative capital and operating costs may be used to determine preferences. A higher level of risk for offshore systems will clearly require the potential for better returns, and hence better capital/operating cost performance for comparative market price of products.

Finally, from a broader perspective, the social and environmental costs of offshore aquaculture development may have to be accounted. In many respects, the removal of aquaculture from highly competed coastal zones may represent a positive economic gain. However, the social costs of making less intensive traditional forms of aquaculture may represent a notable disadvantage in some circumstances.

Conclusions

It appears that many of the potential ingredients for offshore aquaculture are becoming better understood, and the possibilities of developing fully viable and workable production units in open sea conditions are notably more positive than in the past. A number of specific units are on the market and are beginning to establish a proven performance record in physically challenging environments, though the industry still has a substantial number of failures. New production units are still being developed, and although lessons are being learned, a number of these newer designs may prove to be unsatisfactory and may fail.

A key limitation is that offshore aquaculture is not yet considered from a complete systems basis, although as design and operational aspects of various elements are better developed, the opportunity for integrating these should improve, and the complete production system may be defined in terms of its capability to meet commercial performance objectives. On that basis, a number of potential system features could be defined.

At present, most production systems are still conceived as incremental changes from existing inshore systems, and are still linked with understood management and production methods, relying on human perceptions and interactions. While larger systems, particularly in exposed locations, are making increased use of mechanization and remote monitoring, a major challenge for future systems may be to overcome the psychological dependence on human-based management, allowing greater reliance to be placed on automated monitoring, control and management systems.

The economic potential of offshore aquaculture will be a critical determinant for its future development. While arguments for economies of scale in various subsectors are increasingly compelling, and site limitations in inshore areas will make it increasingly difficult for producers to reach these levels of production, the margins of capital and operating cost between inshore and offshore production will need to be minimized. However, present trends suggest that, at least for intensive production of higher value species, offshore production may be expected to grow, and if the expected advantages of good environmental quality in large systems are to be realized, would become more competitive and more significant.

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